

## Method for transmission using a non-uniform interconnection.

### FIELD OF THE INVENTION

5 The invention relates to a method and a device for transmission through interconnections used for sending a plurality of electrical signals, such as the interconnections made with multiconductor cables, or with the traces of a printed circuit board, or inside an integrated circuit.

The French patent application number 09/04610 of 28 September 2009, entitled  
10 “Procédé de transmission utilisant une interconnexion non uniforme” is incorporated by reference.

### PRIOR ART

Let us consider the problem of transmission through an interconnection, for obtaining  $m$  transmission channels,  $m$  being an integer greater than or equal to 2. Each transmission  
15 channel may be used for transmitting signals of any type, for instance analog signals or digital signals, from a source to a destination. We consider here that a digital signal is a signal whose value is defined only at discrete points in time, the set of the values that the signal may take on being discrete. We consider also that each value of a digital signal corresponds to a voltage or current interval. This definition of a digital signal as a “digital signal defined by voltage or  
20 current intervals” includes:

- the binary signals used in binary signaling, that is to say any signal such that, in each transmission channel, the set of the values that this signal may take on has 2 elements;
- the  $N$ -ary signals ( $N$  being an integer greater than or equal to 3) used in multilevel signaling, that is to say any signal such that, in each transmission channel, the set of the values that this  
25 signal may take on has  $N$  elements.

Binary signals are the signals which are the most frequently used today by digital integrated circuits. Multilevel signals, for instance quaternary signals (sometimes referred to as PAM-4 or 4-PAM), are used to obtain high bit rates. We will consider that any signal which does not comply with this definition of a digital signal is an analog signal. Thus, the result of  
30 any type of modulation of a carrier by a digital signal will be regarded as an analog signal.

Said transmission may be obtained through an interconnection comprising  $m + 1$  conductors, among which  $m$  transmission conductors. A device for transmission in such an interconnection is shown in Fig. 1, this device comprising an interconnection (1) having  $m =$   
4 transmission conductors (11) (12) (13) (14) and a reference conductor (7), that is to say a  
35 ground conductor. In Fig. 1, the far-end of the interconnection is connected to a termination

circuit (4). The transmitting circuit (5) receives at its input the signals of the 4 channels of the source (2), and its 5 output terminals are connected to the conductors of the interconnection (1), one of these conductors being ground. The receiving circuit (6) has its 5 input terminals connected to the conductors of the interconnection (1), one of these conductors being ground.

5 The device shown in Fig. 1 provides 4 transmission channels, such that the signals of the 4 channels of the source (2) are sent to the 4 channels of the destination (3). The device shown in Fig. 1 is somewhat general. For instance, according to the case, the transmitting circuit (5) and/or the receiving circuit (6) could comprise no component. However, devices differing from the one shown in Fig. 1 are also conceivable, for instance devices for transmission comprising  
10 several sources and/or several destinations, based on a data bus architecture.

The simplest transmission method for obtaining  $m$  transmission channels uses  $m$  single-ended links. Using  $m$  single-ended links, each transmission channel uses one transmission conductor of the interconnection, and the reference conductor (ground) is used for the return current produced by the currents flowing on the  $m$  transmission conductors. This scheme may  
15 be implemented according to Fig. 1. This method is subject to three detrimental phenomena: echo, internal crosstalk and external crosstalk.

The prior art concerning transmission with reduced echo and internal crosstalk, applicable to this patent application, is set out in the 3 following patents:

- the French patent number 0300064 of 6 January 2003 entitled "Procédé et dispositif pour la  
20 transmission avec une faible diaphonie", corresponding to the international application number PCT/EP2003/015036 of 24 December 2003 (WO 2004/062129), entitled "Method and device for transmission with reduced crosstalk";
- the French patent number 0302814 of 6 March 2003 entitled "Procédé et dispositif numériques pour la transmission avec une faible diaphonie", corresponding to the international  
25 application number PCT/EP2004/002382 of 18 February 2004 (WO 2004/079941), entitled "Digital method and device for transmission with reduced crosstalk";
- the French patent number 0303087 of 13 March 2003 entitled "Procédé et dispositif pour la transmission sans diaphonie", corresponding to the international application number PCT/EP2004/002383 of 18 February 2004 (WO 2004/082168), entitled "Method and device  
30 for transmission without crosstalk".

The inventions described in these three patents may be implemented according to Fig. 1. The article of F. Broydé and E. Clavelier entitled "A New Method for the Reduction of Crosstalk and Echo in Multiconductor Interconnections", published in the journal *IEEE Transactions on Circuits and Systems I*, vol. 52, No. 2, pages 405 to 416, in February 2005,  
35 corrected and supplemented by the article of F. Broydé and E. Clavelier entitled "Corrections to «A New Method for the Reduction of Crosstalk and Echo in Multiconductor Interconnections»", published in the journal *IEEE Transactions on Circuits and Systems I*, vol.

53, No. 8, page 1851 in August 2006, proves that the inventions described in said French patents number 0300064, number 0302814 and number 0303087 and the corresponding international applications are indeed suitable for removing internal crosstalk between the different transmission channels obtained with said interconnection, and also for removing  
 5 echo.

A termination circuit (4) used in one of the inventions disclosed in said French patents number 0300064, number 0302814 and number 0303087, and the corresponding international applications, must be matched to the  $(m + 1)$ -conductor multiconductor transmission line used to model the interconnection. That is to say: the impedance matrix, with respect to ground, of the termination circuit must approximate the characteristic impedance matrix  $\mathbf{Z}_{GC}$ , with respect  
 10 to ground, of said  $(m + 1)$ -conductor multiconductor transmission line ( $\mathbf{Z}_{GC}$  is a matrix of size  $m \times m$ ). Such a termination circuit (4) may for instance correspond to the schematic diagram shown in Fig. 2. The termination circuit (4) shown in Fig. 2 comprises  $m$  signal terminals (41), a reference terminal (ground),  $m$  grounded resistors (401) (402) (403) (404), each of said  
 15 grounded resistors being connected between ground and one and only one of said signal terminals (41), and non-grounded resistors (4012) (4013) (4014) (4023) (4024) (4034), each of said non-grounded resistors being connected between two of said signal terminals (41). Each signal terminal (41) is intended to be connected to a transmission conductor of the interconnection. The termination circuit (4) shown in Fig. 2 is characterized, for the  
 20 interconnection, by an impedance matrix with respect to ground, said impedance matrix with respect to ground being a non-diagonal matrix of size  $m \times m$ . The grounded resistors and the non-grounded resistors are proportioned such that the impedance matrix with respect to ground of the termination circuit (4) approximates said characteristic impedance matrix with respect to ground. Said paper entitled “A New Method for the Reduction of Crosstalk and Echo in  
 25 Multiconductor Interconnections” shows that such a termination can be used to obtain a cancellation of echo and internal crosstalk. Unfortunately, the termination circuit (4) shown in Fig. 2 produces return currents flowing mainly in the reference conductor, a characteristic which conflicts with the reduction of external crosstalk.

Let us note that the ground symbol used in Fig. 2 has exactly the same meaning as the  
 30 other ground symbol used in some of the other accompanying drawings (Figures 1, 5, 10 and 11).

In the case where the destination (3), the termination circuit (4) and the receiving circuit (6) shown in Fig. 1 are built inside an integrated circuit and where the interconnection (1) is built in a printed circuit board to which said integrated circuit is soldered, the French  
 35 patent application number 08/03876 of 8 July 2008 entitled “Dispositif d’interface multicanal avec circuit de terminaison”, corresponding to the international application number PCT/IB2009/051182 of 20 March 2009 (WO 2010/004444), entitled “Multichannel interfacing

device having a termination circuit”, describes (in the first embodiment) the use of the termination circuit shown in Fig. 3. The termination circuit (4) shown in Fig. 3 comprises  $m$  signal terminals (41), a common terminal (40),  $m$  resistors (405) (406) (407) (408) each connected between the common terminal (40) and one and only one of said signal terminals (41), and resistors (4012) (4013) (4014) (4023) (4024) (4034) each connected between two of said signal terminals (41) as in Fig. 2. The receiving circuit (6) has a pseudo-differential input comprising a common terminal. The common terminal nodes of the receiving circuit (6) and of the termination circuit (4) are not grounded inside said integrated circuit. The signal terminals (41) of the termination circuit (4) are intended to be connected to the transmission conductors (11) (12) (13) (14) of the interconnection (1). The common terminal (40) of the termination circuit (4) and the common terminal of the receiving circuit (6) are intended to be connected to said reference conductor (7) of the interconnection (1). The termination circuit (4) shown in Fig. 3 may replace a termination circuit used in one of the devices described in said French patents number 0300064, number 0302814 and number 0303087 and the corresponding international applications, this termination circuit providing a reduction of the external crosstalk caused by the variable power supply currents flowing in the power supply pins of the integrated circuit which are connected to the reference conductor.

The methods disclosed in said French patents number 0300064, number 0302814 and number 0303087 and the corresponding international applications are very effective for reducing echo and internal crosstalk. These methods use an interconnection having  $n$  transmission conductors and a reference conductor (ground), said interconnection being such that it can be modeled, in a part of the frequency band used for transmission, taking into account the lumped impedances seen by the interconnection and caused by the circuits connected to the interconnection elsewhere than at the ends of the interconnection, as a  $(n + 1)$ -conductor uniform multiconductor transmission line, said multiconductor transmission line using natural voltages referenced to ground and natural currents as natural electrical variables, a uniform multiconductor transmission line being a multiconductor transmission line having uniform electrical characteristics over its length.

It is in many cases not possible to build an interconnection which may be modeled, in an suitable part of the frequency band used for transmission, taking into account the lumped impedances seen by the interconnection and caused by the circuits connected to the interconnection elsewhere than at the ends of the interconnection, as such a uniform multiconductor transmission line. This for instance often occurs when the interconnection spreads over several substrates having significantly different dielectric constants.

As an example, Fig. 4 shows the physical configuration of a device for transmission according to the schematic diagram of Fig. 1, in which the transmitting circuit (5) is built in the chip (911) of a first integrated circuit (91) and in which the receiving circuit (6) and the

termination circuit (4) are built in the chip (921) of a second integrated circuit (92). In Fig. 4, the electrical signals must propagate from the transmitting circuit (5) to the receiving circuit (6) through the chip (911) of the first integrated circuit (91), the first level of interconnect (912) of the first integrated circuit (91), the package substrate (913) of the first integrated circuit (91), the second level of interconnect (914) of the first integrated circuit (91), a printed circuit board (90), the second level of interconnect (924) of the second integrated circuit (92), the package substrate (923) of the second integrated circuit (92), the first level of interconnect (922) of the second integrated circuit (92), and the chip (921) of the second integrated circuit (92). In this example, the frequency band of the signals, the physical dimensions of the different items and their electrical characteristics are such that:

- a) the designer must consider an interconnection extending from the location of the transmitting circuit (5) in the chip (911) of the first integrated circuit (91) to the location of the termination circuit (4) in the chip (921) of the second integrated circuit (92);
- b) this interconnection cannot be modeled as a  $(n + 1)$ -conductor uniform multiconductor transmission line, in a suitable part of the frequency band used for transmission;
- c) this interconnection can be modeled, in an suitable part of the frequency band used for transmission, taking into account the lumped impedances seen by the interconnection and caused by the circuits connected to the interconnection elsewhere than at the ends of the interconnection, as a  $(n + 1)$ -conductor non-uniform multiconductor transmission line, a non-uniform multiconductor transmission line being a multiconductor transmission line having non-uniform electrical characteristics over its length.

Unfortunately, if an interconnection cannot be modeled, in a suitable part of the frequency band used for transmission, taking into account the lumped impedances seen by the interconnection and caused by the circuits connected to the interconnection elsewhere than at the ends of the interconnection, as a  $(n + 1)$ -conductor uniform multiconductor transmission line, then the methods disclosed in said French patents number 0300064, number 0302814 and number 0303087, and the corresponding international applications, cannot be used and it can be shown that the propagation of signals generates reflected waves from within the interconnection, such reflections producing echo and internal crosstalk.

## DESCRIPTION OF THE INVENTION

The purpose of the method of the invention is the transmission through a non-uniform interconnection having two or more transmission conductors, the transmission being protected against echo and providing a reduced internal crosstalk.

The invention is about a method for transmitting through an interconnection having  $n$  transmission conductors and a reference conductor (ground),  $n$  being an integer greater than

or equal to 2, said method providing, in a known frequency band,  $m$  transmission channels each corresponding to a signal to be sent from the input of at least one transmitting circuit to the output of at least one receiving circuit, where  $m$  is an integer greater than or equal to 2 and less than or equal to  $n$ , said method comprising the steps of:

- 5 modeling the interconnection in a part of said known frequency band, taking into account the lumped impedances seen by the interconnection and caused by the circuits connected to the interconnection elsewhere than at the ends of the interconnection, as a  $(n + 1)$ -conductor multiconductor transmission line, said multiconductor transmission line using natural voltages referenced to ground and natural currents as natural electrical  
 10 variables, said multiconductor transmission line having a per-unit-length impedance matrix and a per-unit-length admittance matrix which are not both uniform or substantially uniform over the length of said multiconductor transmission line, the characteristic impedance matrix of said multiconductor transmission line being uniform (or substantially uniform) over the length of said multiconductor transmission line;
- 15 coupling the terminals of at least one termination circuit to said reference conductor and to each of said transmission conductors, said at least one termination circuit being, in said part of said known frequency band, approximately characterized, for said interconnection, by an impedance matrix with respect to ground, said impedance matrix with respect to ground being a matrix of size  $n \times n$ .
- 20 Said part of said known frequency band can be any subset of said known frequency band. It is important to clearly distinguish the interconnection, a physical device composed of conductors and dielectrics, from the model which describes some of its properties, which is here the model of the multiconductor transmission line having non-uniform electrical characteristics over its length, also referred to as the model of the non-uniform multiconductor  
 25 transmission line. This model is not capable of describing all interconnections, but it must be suitable for modeling said interconnection, in said part of said known frequency band, with a sufficient accuracy. In this application, any part of an interconnection which is not considered as a conductor is referred to as a dielectric, so that vacuum is a dielectric.

The method of the invention may be such that, in said part of said known frequency  
 30 band, said impedance matrix with respect to ground is a non-diagonal matrix equal to (or substantially equal to) said characteristic impedance matrix.

Said interconnection may be realized without using a cable, for instance an interconnection formed in or on a rigid or flexible printed circuit board (using traces and/or copper areas), or an interconnection formed in or on the substrate of a multi-chip module  
 35 (MCM) or of an hybrid circuit, or an interconnection formed inside a monolithic integrated circuit.

According to the invention, the reference conductor belongs to the interconnection. If

said interconnection is made with a printed circuit board, the reference conductor may be a conductor of the printed circuit board. If said interconnection is made with a cable, the reference conductor may be a conductor of the cable.

It is important to clarify the concept of distinct conductors, in the framework of the theory of multiconductor transmission lines. In the framework of this theory, a conductor may be made of several sufficiently interconnected conductors. This is for instance the case with the stripline structure well known to the person skilled in the art, in which the reference conductor is made of two ground planes connected the one to the other at many points. By the same token, it is appropriate to treat as a single reference conductor a plurality of conductors between which a low impedance is maintained in said part of said known frequency band, at a sufficient number of points along the direction of propagation. As an example, in a multilayer printed circuit board, the traces of an internal layer, used as transmission conductors, may be routed between a conducting plane used as ground (ground plane) and a conducting plane connected to a power supply voltage (power plane). The person skilled in the art knows that, if a low impedance is maintained between these conducting planes by a sufficient number of decoupling capacitors connected between these conducting planes and spread over along said traces of an internal layer, then the two conducting planes, though at different potentials, indeed behave as a single reference conductor for the propagation of signals at sufficiently high frequencies. The wording “reference conductor” may therefore designate several conductors connected to each other at a sufficient number of points along the direction of propagation, through sufficiently low impedances in said part of said known frequency band.

For any integer  $j$  greater than or equal to 1 and less than or equal to  $n$ , at a given curvilinear abscissa (i.e. the arc length measured from the origin), denoted by  $z$ , along the interconnection, let us use  $i_j$  to denote the natural current of index  $j$ , that is to say the current flowing on the transmission conductor number  $j$ , and let us use  $v_{Gj}$  to denote the natural voltage referenced to ground of index  $j$ , that is to say the voltage between the transmission conductor number  $j$  and said reference conductor. We may define the column-vector  $\mathbf{I}_G$  of the natural currents  $i_1, \dots, i_n$  and the column-vector  $\mathbf{V}_G$  of the natural voltages referenced to ground  $v_{G1}, \dots, v_{Gn}$ . In the following, for brevity, we shall use “abscissa” to designate a curvilinear abscissa.

According to the invention, the interconnection is modeled as a  $(n + 1)$ -conductor multiconductor transmission line using said natural voltages referenced to ground and said natural currents as natural electrical variables, with a sufficient accuracy in said part of said known frequency band, taking into account the lumped impedances seen by the interconnection and caused by the circuits connected to the interconnection elsewhere than at the ends of the interconnection. Said  $(n + 1)$ -conductor multiconductor transmission line may nevertheless be defined in the whole known frequency band. At each abscissa  $z$  along the interconnection, at any frequency  $f$  in said known frequency band, said multiconductor

transmission line consequently has a per-unit-length impedance matrix  $\mathbf{Z}_G$  and a per-unit-length admittance matrix  $\mathbf{Y}_G$ . The applicable telegrapher's equations are:

$$\begin{cases} \frac{d \mathbf{V}_G}{dz} = -\mathbf{Z}_G \mathbf{I}_G \\ \frac{d \mathbf{I}_G}{dz} = -\mathbf{Y}_G \mathbf{V}_G \end{cases} \quad (1)$$

The  $(n + 1)$ -conductor multiconductor transmission line defined by the equation (1) uses said natural voltages referenced to ground and said natural currents as variables. These variables are referred to as “natural electrical variables” in contrast to the “modal electrical variables” defined below.  $\mathbf{Z}_G$  and  $\mathbf{Y}_G$  are matrices of size  $n \times n$ .

According to the invention, the per-unit-length impedance matrix  $\mathbf{Z}_G$  and the per-unit-length admittance matrix  $\mathbf{Y}_G$  cannot be considered as both uniform over the length of said multiconductor transmission line, so that said multiconductor transmission line is a non-uniform multiconductor transmission line. In other words, we must consider that  $\mathbf{Z}_G$  and  $\mathbf{Y}_G$  depend on the abscissa  $z$ . Consequently, the classical results concerning uniform multiconductor transmission lines may in general not be transposed to the multiconductor transmission line used to model the interconnection. However, the specialist understands that, at each abscissa  $z$ , it is possible to define a characteristic impedance matrix and transition matrices from modal electrical variables to natural electrical variables, using the same definitions as the ones used, for a uniform multiconductor transmission line, in said articles of F. Broyd  and E. Clavelier published in 2005 and 2006.

At a given abscissa  $z$ ,  $\mathbf{Z}_G$  and  $\mathbf{Y}_G$  being symmetrical matrices,  $\mathbf{Z}_G \mathbf{Y}_G$  and  $\mathbf{Y}_G \mathbf{Z}_G$  have the same eigenvalues, and we shall use  $\mathbf{T}_G$  and  $\mathbf{S}_G$  to denote two invertible matrices such that:

$$\begin{cases} \mathbf{T}_G^{-1} \mathbf{Y}_G \mathbf{Z}_G \mathbf{T}_G = \mathbf{D}_G \\ \mathbf{S}_G^{-1} \mathbf{Z}_G \mathbf{Y}_G \mathbf{S}_G = \mathbf{D}_G \end{cases} \quad (2)$$

where  $\mathbf{D}_G = \text{diag}_n(\gamma_1^2, \dots, \gamma_n^2)$  (3)

is the diagonal matrix of order  $n$  of the eigenvalues of  $\mathbf{Y}_G \mathbf{Z}_G$ . The multiconductor transmission line being non-uniform, we cannot say that each  $\gamma_j$  is a propagation constant of the  $(n + 1)$ -conductor multiconductor transmission line. We note that,  $\mathbf{Z}_G$  and  $\mathbf{Y}_G$  depending on the abscissa  $z$ , it is in general not possible to consider that  $\mathbf{T}_G$  and  $\mathbf{S}_G$  satisfying the equations (2) and (3) define a “modal transform”.

As from the equations (1), (2) and (3), it is possible to define, at a given abscissa  $z$ , a characteristic impedance matrix of said  $(n + 1)$ -conductor multiconductor transmission line, referred to as “characteristic impedance matrix with respect to ground”, or as “characteristic impedance matrix” when no confusion can arise, and denoted by  $\mathbf{Z}_{GC}$ , as:



$$\begin{aligned}\mathbf{Z}_{GC} &= \mathbf{S}_G \Gamma_G^{-1} \mathbf{S}_G^{-1} \mathbf{Z}_G = \mathbf{S}_G \Gamma_G \mathbf{S}_G^{-1} \mathbf{Y}_G^{-1} \\ &= \mathbf{Y}_G^{-1} \mathbf{T}_G \Gamma_G \mathbf{T}_G^{-1} = \mathbf{Z}_G \mathbf{T}_G \Gamma_G^{-1} \mathbf{T}_G^{-1}\end{aligned}\quad (4)$$

where

$$\Gamma_G = \text{diag}_n(\gamma_1, \dots, \gamma_n) \quad (5)$$

is a diagonal matrix of size  $n \times n$ . In general, the characteristic impedance matrix of a non-uniform multiconductor transmission line is a frequency-dependent complex matrix, which also depends on the abscissa  $z$ . However, according to the invention, the  $(n + 1)$ -conductor non-uniform multiconductor transmission line used to model the interconnection is such that the characteristic impedance matrix of said multiconductor transmission line is substantially uniform over its length. Consequently, according to the invention, the characteristic impedance matrix is a frequency-dependent complex matrix of size  $n \times n$ , which substantially does not depend on the abscissa  $z$ . It can be shown that this characteristic is such that the propagation of signals substantially does not generate reflected waves from within the interconnection.

According to the invention, said at least one termination circuit is, in said part of said known frequency band, approximately characterized, for said interconnection, by an impedance matrix with respect to ground. Let us use  $\mathbf{Z}_{GT}$  to denote this impedance matrix with respect to ground. According to the invention,  $\mathbf{Z}_{GT}$  is a matrix of size  $n \times n$ . This indicates that, in said part of said known frequency band, said at least one termination circuit approximately behaves as a  $(n + 1)$ -terminal circuit element having one of its terminals grounded. As said above, according to the invention,  $\mathbf{Z}_{GT}$  may be a non-diagonal square matrix approximately equal to  $\mathbf{Z}_{GC}$ . It can be shown that this characteristic implies that said at least one termination circuit produces very low reflections for all signals propagating inside said  $(n + 1)$ -conductor multiconductor transmission line and incident on the termination circuit.

The method of the invention is particularly advantageous in two circumstances.

In the first circumstance, the method of the invention is such that, at each point along said multiconductor transmission line, in said part of said known frequency band, there exists an invertible matrix, denoted by  $\mathbf{S}$ , such that the inverse of  $\mathbf{S}$  times said per-unit-length impedance matrix times said per-unit-length admittance matrix times  $\mathbf{S}$  is a diagonal matrix (or substantially a diagonal matrix), said matrix  $\mathbf{S}$  being uniform (or substantially uniform) over the length of said multiconductor transmission line. In other words, in the first circumstance, the method of the invention is such that, at each abscissa  $z$  along said multiconductor transmission line, in said part of said known frequency band, there exists a non-singular matrix  $\mathbf{S}$  such that  $\mathbf{S}^{-1} \mathbf{Z}_G \mathbf{Y}_G \mathbf{S}$  is a diagonal matrix (or substantially a diagonal matrix), said matrix  $\mathbf{S}$  being independent (or substantially independent) of the abscissa  $z$  along said multiconductor transmission line. Clearly, the matrix  $\mathbf{S}_G = \mathbf{S}$  satisfies the second line of equation (2) and is independent of  $z$ . Let us use  ${}^t\mathbf{A}$  to denote the transpose of a matrix  $\mathbf{A}$ . The

matrices  $\mathbf{Z}_G$  and  $\mathbf{Y}_G$  being symmetrical, we observe that the matrix  $\mathbf{T}_G$  given by

$$\mathbf{T}_G = {}^t\mathbf{S}_G^{-1} \quad (6)$$

is a solution of the first line of the equation (2) and is independent of  $z$ . Using this choice of a matrix  $\mathbf{S}_G$  and of a matrix  $\mathbf{T}_G$ , we may define the column-vector  $\mathbf{V}_{GM}$  and the column-vector

5  $\mathbf{I}_{GM}$ , given by:

$$\begin{cases} \mathbf{V}_G = \mathbf{S}_G \mathbf{V}_{GM} \\ \mathbf{I}_G = \mathbf{T}_G \mathbf{I}_{GM} \end{cases} \quad (7)$$

We note that, in the first circumstance, the method of the invention is such that, at each point along said multiconductor transmission line, in said part of said known frequency band, there exists an invertible matrix, denoted by  $\mathbf{T}$ , such that the inverse of  $\mathbf{T}$  times said per-unit-length admittance matrix times said per-unit-length impedance matrix times  $\mathbf{T}$  is a diagonal matrix (or substantially a diagonal matrix), said matrix  $\mathbf{T}$  being uniform (or substantially uniform) over the length of said multiconductor transmission line.

The matrices  $\mathbf{Z}_{GC}$ ,  $\mathbf{S}_G$  and  $\mathbf{T}_G$  being independent of  $z$ , it can then be shown that the second-order differential equations satisfied by the new variables  $\mathbf{V}_{GM}$  and  $\mathbf{I}_{GM}$  are

$$15 \quad \begin{cases} \frac{d^2 \mathbf{V}_{GM}}{dz^2} - \Gamma_G^2 \mathbf{V}_{GM} = \frac{d \Gamma_G}{dz} \Gamma_G^{-1} \frac{d \mathbf{V}_{GM}}{dz} \\ \frac{d^2 \mathbf{I}_{GM}}{dz^2} - \Gamma_G^2 \mathbf{I}_{GM} = \frac{d \Gamma_G}{dz} \Gamma_G^{-1} \frac{d \mathbf{I}_{GM}}{dz} \end{cases} \quad (8)$$

Clearly,  $\Gamma_G$  and  $d \Gamma_G / dz$  being diagonal matrices, these differential equations are decoupled, so that we have achieved a modal decomposition. Consequently, in the first circumstance, we can consider that  $\mathbf{I}_{GM}$  is the column-vector of the  $n$  modal currents  $i_{GM1}, \dots, i_{GMn}$ , that  $\mathbf{V}_{GM}$  is the column-vector of the  $n$  modal voltages  $v_{GM1}, \dots, v_{GMn}$ , and that the  $\gamma_i$  are the propagation constants of the different propagation modes of said  $(n + 1)$ -conductor multiconductor transmission line.

Consequently, if  $\mathbf{S}_G = \mathbf{S}$  and if  $\mathbf{T}_G$  is given by equation (6), we will refer to  $\mathbf{S}_G$  as the “transition matrix from modal voltages to natural voltages” and we will refer to  $\mathbf{T}_G$  as the “transition matrix from modal currents to natural currents” (for comparison with said French patent application number 09/04610, it is useful to note that the transition matrix from the basis C to the basis B is called “matrice de passage de la base B à la base C ” in French). The wording “modal electrical variable” will indiscriminately designate a modal current or a modal voltage. The matrices  $\mathbf{S}_G$  and  $\mathbf{T}_G$  are therefore the transition matrices from modal electrical variables to natural electrical variables.

In the first circumstance, it can be shown that echo and internal crosstalk are very effectively reduced if the method of the invention further comprises the steps of:

- using one said transmitting circuit receiving  $m$  “input signals of the transmitting circuit” corresponding each to a transmission channel, the output of said transmitting circuit being coupled to the  $n$  transmission conductors, the output of said transmitting circuit delivering modal electrical variables defined by a transition matrix from modal electrical variables to natural electrical variables, said transition matrix from modal electrical variables to natural electrical variables being equal to said matrix  $\mathbf{S}$  or to the inverse of the transpose of said matrix  $\mathbf{S}$ , each of said modal electrical variables being mainly determined by one and only one of said “input signals of the transmitting circuit”; and
- 10 using one said receiving circuit delivering  $m$  “output signals of the receiving circuit” corresponding each to a transmission channel, the input of said receiving circuit being coupled to the  $n$  transmission conductors, each of said “output signals of the receiving circuit” being mainly determined by one and only one of said modal electrical variables defined by said transition matrix from modal electrical variables to natural electrical variables.

15 In the first circumstance, the output of one of said transmitting circuits delivers modal electrical variables, said modal electrical variables being defined by said transition matrix from modal electrical variables to natural electrical variables of said  $(n + 1)$ -conductor multiconductor transmission line, each of said modal electrical variables being mainly determined by one and only one of said “input signals of the transmitting circuit”. This must be interpreted in a broad sense, as: each of said modal electrical variables is mainly determined, at each point in time, by the history, up to said point in time, of one and only one of said “input signals of the transmitting circuit”. The use of either modal currents or modal voltages as modal electrical variables being without physical effect, let us for instance use

20 modal voltages as modal electrical variables. In this case,  $\mathbf{V}_{GM}$  produced by said one of said transmitting circuits is determined, at each point in time, by the history, up to said point in time, of said “input signals of the transmitting circuit”. Therefore, using equation (7), we see that, at each frequency  $f$  in said known frequency band, said one of said transmitting circuits must produce, at its point of connection to the interconnection, on each transmission conductor,

25 the natural voltages referenced to ground of the column-vector  $\mathbf{V}_G(f)$  given by:

$$\mathbf{V}_G(f) = \mathbf{S}_G(f) \mathbf{V}_{GM}(f) \quad (9)$$

where we write the frequency dependence to designate frequency domain quantities, and where the Fourier transform

$$\mathbf{V}_{GM}(f) = \int_{-\infty}^{+\infty} \mathbf{V}_{GM}(t) e^{-2i\pi ft} dt \quad (10)$$

gives the frequency domain vector  $\mathbf{V}_{GM}(f)$  as a function of the time domain vector  $\mathbf{V}_{GM}(t)$  at a given point in time  $t$ . We also see that, at each point in time  $t$ , said one of said transmitting circuits must produce, on each conductor, at its point of connection to the interconnection, the natural voltages referenced to ground of the column-vector  $\mathbf{V}_G(t)$  given by the inverse Fourier transform

$$\mathbf{V}_G(t) = 2 \operatorname{Re} \left[ \int_0^{+\infty} \mathbf{V}_G(f) e^{2i\pi ft} df \right] \quad (11)$$

where the integration over all positive frequencies may of course be replaced by an integration over said known frequency band. Consequently, causality implies that each of said natural voltages referenced to ground is mainly determined, at each point in time, by the history, up to said point in time, of said “input signals of the transmitting circuit”.

In the first circumstance, one of said receiving circuits delivers “output signals of the receiving circuit”, each of said “output signals of the receiving circuit” being mainly determined by one and only one of said modal electrical variables, said modal electrical variables being defined by said transition matrix from modal electrical variables to natural electrical variables of said  $(n + 1)$ -conductor multiconductor transmission line. This must be interpreted in a broad sense, as: each of said “output signals of the receiving circuit” is mainly determined, at each point in time, by the history, up to said point in time, of one and only one of said modal electrical variables. The use of either modal currents or modal voltages as modal electrical variables being without physical effect, let us for instance use modal voltages as modal electrical variables. In this case, said “output signals of the receiving circuit” are mainly determined, at each point in time, by the history, up to said point in time, of  $\mathbf{V}_{GM}$  at the input of said one of said receiving circuits. We also see that said one of said receiving circuits must, at each point in time  $t$ , use the column-vector  $\mathbf{V}_{GM}(t)$  given by the inverse Fourier transform

$$\mathbf{V}_{GM}(t) = 2 \operatorname{Re} \left[ \int_0^{+\infty} \mathbf{V}_{GM}(f) e^{2i\pi ft} df \right] \quad (12)$$

where we write the frequency dependence to designate frequency domain vectors, and where, according to equation (7),  $\mathbf{V}_{GM}(f)$  is given by

$$\mathbf{V}_{GM}(f) = \mathbf{S}_G^{-1}(f) \mathbf{V}_G(f) \quad (13)$$

In equation (12), the integration over all positive frequencies may of course be replaced by an integration over said known frequency band. Since said one of said receiving circuits must sense on the interconnection, at its point of connection to the interconnection, the natural voltages referenced to ground, we see that the column-vector  $\mathbf{V}_G(f)$  used in equation (13) is given by the Fourier transform

$$\mathbf{V}_G(f) = \int_{-\infty}^{+\infty} \mathbf{V}_G(t) e^{-2i\pi ft} dt \quad (14)$$

Consequently, causality implies that each of said “output signals of the receiving circuit” is mainly determined, at each point in time, by the history, up to said point in time, of  $\mathbf{V}_G$  at the input of said one of said receiving circuits.

5 In the second circumstance, the method of the invention is such that, at each point along said multiconductor transmission line, in said part of said known frequency band, the product of said per-unit-length impedance matrix and said per-unit-length admittance matrix is equal (or substantially equal) to the product of a scalar and the identity matrix of order  $n$ . In the second circumstance, at each abscissa  $z$  along said multiconductor transmission line, in said  
10 part of said known frequency band, we may write

$$\mathbf{Y}_G \mathbf{Z}_G = \mathbf{Z}_G \mathbf{Y}_G = \gamma^2 \mathbf{I}_n \quad (15)$$

where  $\mathbf{I}_n$  is the identity matrix of order  $n$  and where  $\gamma$  is said scalar, said scalar being a complex number which may be frequency-dependent and which may depend on  $z$ . As a consequence, the matrices  $\mathbf{T}_G$  and  $\mathbf{S}_G$  defined by the equation (2) may be chosen equal to the identity matrix  
15 of order  $n$ . Consequently, any natural electrical variable may also, in this second circumstance, be regarded as a modal electrical variable.

As from the equations (1) to (5) and (15), it is possible to show that the characteristic impedance matrix is given by:

$$\mathbf{Z}_{GC} = \frac{1}{\gamma} \mathbf{Z}_G = \gamma \mathbf{Y}_G^{-1} \quad (16)$$

20 In the second circumstance, it can be shown that echo and internal crosstalk are very effectively reduced if the method of the invention further comprises the steps of:

using one said transmitting circuit receiving  $m$  “input signals of the transmitting circuit” corresponding each to a transmission channel, the output of said transmitting circuit being coupled to at least  $m$  of said transmission conductors, the output of said  
25 transmitting circuit delivering natural electrical variables, each of said natural electrical variables being mainly determined by one and only one of said “input signals of the transmitting circuit”; and

using one said receiving circuit delivering  $m$  “output signals of the receiving circuit” corresponding each to a transmission channel, the input of said receiving circuit being  
30 coupled to at least  $m$  of said transmission conductors, each of said “output signals of the receiving circuit” being mainly determined by said natural electrical variables.

In the second circumstance, the output of one of said transmitting circuits delivers natural electrical variables, each of said natural electrical variables being mainly determined by one and only one of said “input signals of the transmitting circuit”. This must be interpreted

in a broad sense, as: each of said natural electrical variables is mainly determined, at each point in time, by the history, up to said point in time, of one and only one of said “input signals of the transmitting circuit”.

In the second circumstance, one of said receiving circuits delivers “output signals of the receiving circuit”, each of said “output signals of the receiving circuit” being mainly determined by said natural electrical variables. This must be interpreted in a broad sense, as: each of said “output signals of the receiving circuit” is mainly determined, at each point in time, by the history, up to said point in time, of said natural electrical variables.

The specialists know, for instance from a computation based on the geometry of the conductors and dielectrics, on the conductivity of the conductors and on the permittivity and the losses of the dielectrics, how to determine the matrices  $\mathbf{Z}_G$  and  $\mathbf{Y}_G$  of a multiconductor transmission line used for modeling the interconnection and the reference conductor, as a function of frequency and of  $z$ . The specialists also know how to measure these matrices. It is therefore clear that it is possible to proportion the conductors of a suitable structure such that:

- the matrix  $\mathbf{Z}_{GC}$  is substantially independent of  $z$  ;
- one obtains a matrix  $\mathbf{Z}_{GC}$  approximating, in said part of said known frequency band, a wanted matrix.

Consequently, the method of the invention may be such that, prior to modeling said interconnection, one proportions said interconnection in such a way that it may, with a sufficient accuracy in said part of said known frequency band, taking into account the lumped impedances seen by the interconnection and caused by the circuits connected to the interconnection elsewhere than at the ends of the interconnection, be modeled as a  $(n + 1)$ -conductor multiconductor transmission line, said multiconductor transmission line using the natural voltages referenced to ground and the natural currents as natural electrical variables, the characteristic impedance matrix of said multiconductor transmission line being uniform (or substantially uniform) over its length.

Note that, in many cases, we can consider that, when computing the matrices  $\mathbf{Z}_{GC}$ ,  $\mathbf{S}_G$  and  $\mathbf{T}_G$  of said  $(n + 1)$ -conductor multiconductor transmission line, the losses are negligible in some frequency bands, for instance when said part of said known frequency band is above 1 MHz. In this case, in said part of said known frequency band,  $\mathbf{Z}_{GC}$  is real and frequency-independent, and the matrices  $\mathbf{S}_G$  and  $\mathbf{T}_G$  may be chosen real and frequency-independent. At lower frequencies, for instance when said part of said known frequency band contains frequencies below 1 MHz, losses are often not negligible and  $\mathbf{Z}_{GC}$  cannot be considered as real, which obviously leads to a more complex implementation of the method of the invention. However, this question can often be disregarded, because internal crosstalk and echo at low frequencies may in many cases be ignored, and because, in these cases, it may be of no importance that the termination circuits present an impedance matrix near  $\mathbf{Z}_{GC}$  at these low

frequencies. Consequently, said part of said known frequency band will often be contained in the interval of the frequencies ranging from 1 MHz to 100 GHz.

However, the frequency above which losses may possibly be neglected for the computation of the matrices  $\mathbf{Z}_{GC}$ ,  $\mathbf{S}_G$  and  $\mathbf{T}_G$  of said  $(n + 1)$ -conductor multiconductor transmission line depends on the shape and position of the conductors in a section of the interconnection in a plane orthogonal to the direction of propagation, and on the conductivity of the conductors. We note that in the case of on-chip interconnects, this frequency may be much higher than 1 MHz, for instance above 1 GHz.

Since, according to the invention, the properties of said  $(n + 1)$ -conductor multiconductor transmission line may be defined arbitrarily outside said part of said known frequency band, it is possible to obtain that  $\mathbf{Z}_{GC}$ ,  $\mathbf{S}_G$  and  $\mathbf{T}_G$  are real and frequency-independent over said known frequency band, when  $\mathbf{Z}_{GC}$ ,  $\mathbf{S}_G$  and  $\mathbf{T}_G$  are real and frequency-independent over said part of said known frequency band. When  $\mathbf{Z}_{GC}$  is real and frequency-independent over said known frequency band, we obtain the following consequence which simplifies the design of a device for implementing the method of the invention: the matrix  $\mathbf{Z}_{GC}$  may be realized with a network of  $n(n + 1)/2$  resistors or less. When  $\mathbf{S}_G$  and  $\mathbf{T}_G$  are real and frequency-independent over said known frequency band, we obtain the following consequences which simplify the design of a device for implementing the method of the invention in the first circumstance:

a) the equations (9), (10) and (11) defining the operation of a transmitting circuit become

$$\mathbf{V}_G(t) = \mathbf{S}_G \mathbf{V}_{GM}(t) \quad (17)$$

b) the equations (12), (13) and (14) defining the operation of a receiving circuit become

$$\mathbf{V}_{GM}(t) = \mathbf{S}_G^{-1} \mathbf{V}_G(t) \quad (18)$$

The specialist understands that a termination circuit having, at a given frequency, an impedance matrix equal to  $\mathbf{Z}_{GC}$  may be composed of  $n(n + 1)/2$  passive linear two-terminal circuits elements,  $n$  of said passive linear two-terminal circuit elements being each connected between the reference conductor and one and only one of said transmission conductors,  $n(n - 1)/2$  of said passive linear two-terminal circuit elements being each connected between two of said transmission conductors. However, the specialist also understands that a termination circuit providing, at a given frequency, an impedance matrix close enough to  $\mathbf{Z}_{GC}$  may often be composed of less than  $n(n + 1)/2$  passive linear two-terminal circuit elements. The suitability of a given termination circuit may for instance be determined using a suitable norm of the matrix  $\mathbf{Z}_{GT} - \mathbf{Z}_{GC}$ . For instance, a termination circuit may be proportioned such that all components of the matrix  $\mathbf{Z}_{GT} - \mathbf{Z}_{GC}$  have an absolute value less than a sufficiently small

arbitrary value, for instance 3 Ohms. However, it is often more appropriate to determine the suitability of a given termination circuit using a suitable norm of the matrix of the voltage reflection coefficients, with respect to ground, of said termination circuit, denoted by  $\mathbf{P}_G$  and given by

$$\mathbf{P}_G = (\mathbf{Z}_{GT} - \mathbf{Z}_{GC})(\mathbf{Z}_{GT} + \mathbf{Z}_{GC})^{-1} \quad (19)$$

For instance, at least one termination circuit may be proportioned such that, in said part of said known frequency band, each component of the matrix  $\mathbf{P}_G$  has an absolute value less than or equal to a sufficiently small arbitrary value, for instance 5/100.

In order that the invention provides the desired characteristics, it is important that the interconnection behaves, in said part of said known frequency band, taking into account the lumped impedances seen by the interconnection and caused by the circuits connected to the interconnection elsewhere than at the ends of the interconnection, as a  $(n + 1)$ -conductor multiconductor transmission line, the characteristic impedance matrix of said multiconductor transmission line being substantially uniform over its length, said multiconductor transmission line using said natural voltages referenced to ground and said natural currents as natural electrical variables. In some cases, in order to take into account the lumped impedances seen by the interconnection and caused by the circuits connected to it elsewhere than at its ends, the designer need only observe that they are not present or that they may be ignored. In other cases, in order to take into account the lumped impedances seen by the interconnection and caused by the circuits connected to it elsewhere than at its ends, the designer must quantitatively consider these lumped impedances to obtain that said characteristic impedance matrix is sufficiently uniform over the length of said multiconductor transmission line.

The function of the termination circuits is to ensure that no reflection of an incident signal occurs at a disturbing level, at an end of the interconnection, for the signals propagating in said  $(n + 1)$ -conductor multiconductor transmission line, in said part of said known frequency band. It is clear that the lower the desired maximum crosstalk coupling level, the lower the level of reflection of incident signals which has to be regarded as disturbing, and that, in order not to exceed this level, it must be specified that the termination circuit must have a matrix  $\mathbf{Z}_{GT}$  closer to  $\mathbf{Z}_{GC}$ .

According to the invention, in order to ensure that no reflection of an incident signal occurs at a disturbing level at an end of the interconnection for the signals propagating in said  $(n + 1)$ -conductor multiconductor transmission line, the specialist understands that it is sufficient, when one or more transmitting circuits are connected at a single end of the interconnection, to arrange a termination circuit at the other end of the interconnection. The specialist also sees that in all other cases, that is to say when a transmitting circuit is connected elsewhere than at one end of the interconnection, and/or when transmitting circuits are



connected at both ends of the interconnection, it is necessary to arrange termination circuits at both ends of the interconnection. Thus, according to the method of the invention, we may either arrange a termination circuit at one end only of the interconnection, or arrange a termination circuit at each end of the interconnection.

5 According to the invention, the number  $m$  of transmission channels between any one of the transmitting circuits and any one of the receiving circuits may be equal to the number  $n$  of transmission conductors. This method is preferred because it is generally the most economical. However, it is also conceivable to use a number  $n$  of transmission conductors that is greater than the number  $m$  of transmission channels.

10 We now describe a device for proportioning a device for implementing the method of the invention. A device for proportioning a device for transmitting through an interconnection having  $n$  transmission conductors and a reference conductor,  $n$  being an integer greater than or equal to 2, said device for transmitting through an interconnection providing, in a known frequency band,  $m$  transmission channels, where  $m$  is an integer greater than or equal to 2 and  
15 less than or equal to  $n$ , may comprise:

means for modeling the interconnection, to a sufficient accuracy in a part of said known frequency band, taking into account the lumped impedances seen by the interconnection and caused by the circuits connected to the interconnection elsewhere than at the ends of the interconnection, as a  $(n + 1)$ -conductor multiconductor  
20 transmission line, said multiconductor transmission line using the natural voltages referenced to ground and the natural currents as natural electrical variables, said multiconductor transmission line having a per-unit-length impedance matrix and a per-unit-length admittance matrix which are not both uniform (or substantially uniform) over the length of said multiconductor transmission line, the characteristic impedance  
25 matrix of said multiconductor transmission line being uniform (or substantially uniform) over the length of said multiconductor transmission line;

means for proportioning a termination circuit, said termination circuit being, in said part of said known frequency band, approximately characterized, for said interconnection, by an impedance matrix with respect to ground, said impedance matrix with respect to  
30 ground being a non-diagonal matrix of size  $n \times n$  substantially equal to said characteristic impedance matrix.

Said device for proportioning a device for transmitting through an interconnection having  $n$  transmission conductors and a reference conductor may comprise a computer running a suitable program.

35 Said device for proportioning a device for transmitting through an interconnection having  $n$  transmission conductors and a reference conductor may be such that the means for modeling the interconnection comprise means for measuring and/or for computing the real

electrical characteristics of the interconnection, based on the relative layout of the transmission conductors and of the reference conductor and on the characteristics of the dielectrics surrounding them.

We now describe a device for implementing the method of the invention. A device for  
 5 transmission providing, in a known frequency band,  $m$  transmission channels each corresponding to a signal to be sent from the input of at least one transmitting circuit to the output of at least one receiving circuit, where  $m$  is an integer greater than or equal to 2, comprises:

an interconnection having  $n$  transmission conductors and a reference conductor (ground),  $n$   
 10 being an integer greater than or equal to  $m$ , the interconnection being modeled (to a sufficient accuracy), in a part of said known frequency band, taking into account the lumped impedances seen by the interconnection and caused by the circuits connected to the interconnection elsewhere than at the ends of the interconnection, as a  $(n + 1)$ -conductor multiconductor transmission line, said multiconductor transmission line  
 15 using the natural voltages referenced to ground and the natural currents as natural electrical variables, said multiconductor transmission line having a per-unit-length impedance matrix and a per-unit-length admittance matrix which are not both uniform or substantially uniform over the length of said multiconductor transmission line, the characteristic impedance matrix of said multiconductor transmission line being uniform  
 20 (or substantially uniform) over the length of said multiconductor transmission line;

at least one termination circuit coupled to the reference conductor and to each of said  
 transmission conductors, said at least one termination circuit being, when said at least  
 one termination circuit is in the activated state, approximately characterized, for said  
 interconnection, at at least one quiescent operating point, for small signals in said part  
 25 of said known frequency band, by an impedance matrix with respect to ground, denoted by  $\mathbf{Z}_{GT}$ , said impedance matrix with respect to ground being a non-diagonal matrix of size  $n \times n$  equal to (or substantially equal to) said characteristic impedance matrix.

In the following, the wordings “is in the deactivated state” and “is not in the activated  
 state” are equivalent. According to the invention, it is possible that there is a deactivated state  
 30 for one or more of said termination circuits, in which the behavior of this termination circuit is different from the one defined above. However, the existence of a deactivated state for one or more of said termination circuits is not at all a characteristic of the invention.

In the first circumstance, a device for implementing the method of the invention may  
 be such that, at each point along said multiconductor transmission line, in said part of said  
 35 known frequency band, there exists an invertible matrix, denoted by  $\mathbf{S}$ , such that the inverse of  $\mathbf{S}$  times said per-unit-length impedance matrix times said per-unit-length admittance matrix times  $\mathbf{S}$  is a diagonal matrix (or substantially a diagonal matrix), said matrix  $\mathbf{S}$  being uniform

(or substantially uniform) over the length of said multiconductor transmission line, said device for implementing the method of the invention further comprising:

at least one said transmitting circuit receiving  $m$  “input signals of the transmitting circuit” corresponding each to a transmission channel, the output of said at least one said transmitting circuit being coupled to the  $n$  transmission conductors, the output of said at least one said transmitting circuit delivering modal electrical variables when said at least one said transmitting circuit is in the activated state, said modal electrical variables being defined by a transition matrix from modal electrical variables to natural electrical variables, said transition matrix from modal electrical variables to natural electrical variables being equal to said matrix  $\mathbf{S}$  or to the inverse of the transpose of said matrix  $\mathbf{S}$ , each of said modal electrical variables being mainly determined by one and only one of said “input signals of the transmitting circuit”; and

at least one said receiving circuit delivering, when said at least one said receiving circuit is in the activated state,  $m$  “output signals of the receiving circuit” corresponding each to a transmission channel, the input of said at least one said receiving circuit being coupled to the  $n$  transmission conductors, each of said “output signals of the receiving circuit” being mainly determined by one and only one of said modal electrical variables defined by said transition matrix from modal electrical variables to natural electrical variables.

In the second circumstance, a device for implementing the method of the invention may be such that, at each point along said multiconductor transmission line, in said part of said known frequency band, the product of said per-unit-length impedance matrix and said per-unit-length admittance matrix is equal (or substantially equal) to the product of a scalar and the identity matrix of order  $n$ , said device for implementing the method of the invention further comprising:

at least one said transmitting circuit receiving  $m$  “input signals of the transmitting circuit” corresponding each to a transmission channel, the output of said at least one said transmitting circuit being coupled to at least  $m$  of said transmission conductors, the output of said at least one said transmitting circuit delivering natural electrical variables when said at least one said transmitting circuit is in the activated state, each of said natural electrical variables being mainly determined by one and only one of said “input signals of the transmitting circuit”; and

at least one said receiving circuit delivering, when said at least one said receiving circuit is in the activated state,  $m$  “output signals of the receiving circuit” corresponding each to a transmission channel, the input of said at least one said receiving circuit being coupled to at least  $m$  of said transmission conductors, each of said “output signals of the receiving circuit” being mainly determined by one and only one of said natural

electrical variables.

According to the invention, it is possible that there is a deactivated state for one or more of said transmitting circuits, in which the behavior of this transmitting circuit is different from the ones defined above. However, the existence of a deactivated state for one or more of said transmitting circuits is not at all a characteristic of the invention. According to the invention, it is possible that there is a deactivated state for one or more of said receiving circuits, in which the behavior of this receiving circuit is different from the ones defined above. However, the existence of a deactivated state for one or more of said receiving circuits is not at all a characteristic of the invention.

According to the invention, the “input signals of the transmitting circuit” may be analog signals or digital signals. A transmitting circuit used in a device for implementing the method of the invention may use analog signal processing and/or digital signal processing to deliver said natural or modal electrical variables. According to the invention, the “output signals of the receiving circuit” may be analog signals or digital signals. A receiving circuit used in a device for implementing the method of the invention may use analog signal processing and/or digital signal processing to deliver said “output signals of the receiving circuit”.

For a termination circuit used in a device for implementing the method of the invention, the requirement relating to  $\mathbf{Z}_{GT}$ , namely that  $\mathbf{Z}_{GT}$  must be a non-diagonal matrix of size  $n \times n$  approximately equal to  $\mathbf{Z}_{GC}$ , should be applicable to the normal operation of the device for implementing the method of the invention. Said quiescent operating point chosen for determining  $\mathbf{Z}_{GT}$  should therefore be such that the quiescent voltages between each of said transmission conductors and ground have values which may appear at a given point in time under normal operation.

A termination circuit used in a device for implementing the method of the invention may be such that it behaves as a linear circuit for the interconnection. Consequently, said at least one termination circuit coupled to said reference conductor and to each of said transmission conductors may be such that said at least one termination circuit is, in said part of said known frequency band, when said at least one termination circuit is in the activated state, approximately characterized, for said interconnection, by an impedance matrix with respect to ground, said impedance matrix with respect to ground being a non-diagonal matrix of size  $n \times n$  approximately equal to said characteristic impedance matrix.

In a device for implementing the method of the invention, it is possible that the number  $m$  of transmission channels between one of said transmitting circuits and one of said receiving circuits is equal to the number  $n$  of transmission conductors. Such a device is preferred because it provides the largest number of transmission channels for a given interconnection. However, it is also conceivable to use a number  $n$  of transmission conductors greater than the number  $m$  of transmission channels. In particular,  $n$  may be greater than or equal to three.

In a device for implementing the method of the invention, it is possible that each of said termination circuits is arranged at an end of said interconnection. This arrangement is preferred because specialists understand that it is the best technique for eliminating reflections of signals propagating in said  $(n + 1)$ -conductor multiconductor transmission line.

5 A device for implementing the method of the invention may be such that said termination circuits, said transmitting circuits and said receiving circuits are without any part in common to any two of them. Conversely, a device for implementing the method of the invention may be such that said termination circuits, said transmitting circuits and said receiving circuits are not without any part in common to any two of them.

10 A device for implementing the method of the invention may be such that at least one said termination circuit is made of a network of resistors,  $n$  of said resistors being each connected between one of said transmission conductors and ground, one or more of said resistors being each connected between two of said transmission conductors. For  $n = 4$ , a non-limiting example of such a termination circuit is shown in Fig. 2 (Fig. 2 being presented above, 15 in the prior art section).

A termination circuit made of a network of resistors is however not at all a characteristic of the invention. By way of a first example, designers may, in order to reduce the power consumed by one of said termination circuits, choose to allow this termination circuit to be effective only in a relevant interval of frequencies, for instance by including 20 suitable reactive circuit elements in this termination circuit. By way of a second example, one of said termination circuits could include active components, for instance insulated gate field-effect transistors (MOSFETs) operating in the ohmic regime. The impedance of the channel of such components may be adjustable by an electrical means. Consequently, a device for implementing the method of the invention may be such that the impedance matrix with respect 25 to ground, of at least one said termination circuit in the activated state, can be adjusted by electrical means.

In the case where one of said termination circuits has an activated state and a deactivated state, the impedance of the channel of one or more MOSFETs may for instance be controlled by one or more control signals taking on different values in the activated state and 30 in the deactivated state. Consequently, at least one of said termination circuits may be such that said termination circuit has an activated state and a deactivated state, the impedance matrix, with respect to ground, of said termination circuit in the activated state being different from the impedance matrix, with respect to ground, of said termination circuit in the deactivated state.

35 In the case where one of said termination circuits has an activated state and a deactivated state, components such as transistors may for instance be used as switches having a closed state and an open state. In this case, said transistors may for instance be in the closed

state when this termination circuit is in the activated state, and be in the open state when this termination circuit is in the deactivated state. Consequently, it is possible that at least one said termination circuit has an activated state and a deactivated state, each current flowing from said at least one said termination circuit to one of said transmission conductors being substantially zero when said at least one said termination circuit is in the deactivated state. Designers may, in order to reduce the power consumed by such a termination circuit, choose to put this termination circuit in the deactivated state when a transmitting circuit close to the termination circuit is in the activated state.

In the case where a termination circuit of a device for implementing the method of the invention is built inside an integrated circuit, it is possible to use a termination circuit comprising a common terminal, in a manner similar to the use described in the first embodiment of said French patent application number 08/03876 and the corresponding international application. For  $n = 4$ , a non-limiting example of such a termination circuit is shown in Fig. 3 (Fig. 3 being presented above, in the prior art section). In this case, the common terminal node of the termination circuit is not grounded inside said integrated circuit, but the common terminal of the termination circuit is nevertheless coupled to the reference conductor of the interconnection, as explained above.

In the first circumstance, for the design of a transmitting circuit or of a receiving circuit, it is possible to use the design equations presented in the Section V of said article entitled “A New Method for the Reduction of Crosstalk and Echo in Multiconductor Interconnections”, even though this paper only considers the case where a uniform multiconductor transmission line can be used to model the interconnection. In the second circumstance, for the design of a transmitting circuit or of a receiving circuit, it is possible to use the design equations presented in the Table I of the article of F. Broyd  and E. Clavelier entitled “Echo-Free and Crosstalk-Free Transmission in Particular Interconnections” published in the *IEEE Microwave and Wireless Components Letters*, Vol. 19, No. 4, pages 209 to 211, in April 2009, even though this paper only considers the case where a uniform multiconductor transmission line can be used to model the interconnection.

In the case where a receiving circuit of a device for implementing the method of the invention is built inside an integrated circuit, it is possible to use a receiving circuit having a pseudo-differential input comprising a common terminal, in a manner similar to the use described in the first embodiment of said French patent number 08/03876 and the corresponding international application. In this case, the common terminal node of the receiving circuit is not grounded inside said integrated circuit, but the common terminal of the receiving circuit is nevertheless coupled to the reference conductor of the interconnection, as explained above.

According to the invention, one or more of said transmitting circuits and/or one or more

of said receiving circuits may have a filtering function, for instance for the purpose of obtaining a pre-emphasis, a de-emphasis or an equalization improving transmission. It then becomes necessary to synthesize the corresponding filters, either as analog filters or as digital filters, using one of the many methods known to specialists.

5           When losses are not negligible in the interconnection, phase and amplitude distortions may occur, which are referred to as distortions caused by propagation. The reduction of these distortions may be obtained, in a device for implementing the method of the invention, using an equalization reducing the effects of the distortions caused by propagation, said equalization being implemented in one or more of said transmitting circuits and/or in one or more of said  
10 receiving circuits. This type of processing, which is also sometimes referred to as compensation, is well known to specialists and may be implemented using analog signal processing or digital signal processing.

Specialists know that it is commonplace to use adaptive algorithms for implementing this type of processing in receivers for data transmission. A device for implementing the  
15 method of the invention may use an adaptive equalization. This type of processing is well known to specialists and is often implemented using digital signal processing.

## BRIEF DESCRIPTION OF THE DRAWINGS

Other advantages and characteristics of the invention will appear more clearly from the following description of particular embodiments of the invention, given by way of non-limiting  
20 examples, with reference to the accompanying drawings in which:

- Figure 1 shows a device for transmission comprising an interconnection having four transmission conductors, and has already been discussed in the section dedicated to the presentation of prior art;
- Figure 2 shows a first termination circuit which may be used in the device for  
25 transmission shown in Fig. 1, and has already been discussed in the section dedicated to the presentation of prior art;
- Figure 3 shows a second termination circuit which may be used in the device for transmission shown in Fig. 1, and has already been discussed in the section dedicated to the presentation of prior art;
- Figure 4 shows the physical configuration of a device for transmission, and has  
30 already been discussed in the section dedicated to the presentation of prior art;
- Figure 5 shows a first embodiment of the invention;
- Figure 6 shows a cross section of the interconnection used in the first embodiment;
- Figure 7 shows a cross section of the interconnection used in a second  
35

embodiment;

- Figure 8 shows a cross section of the interconnection used in the first embodiment, with indication of several dimensional parameters;
- Figure 9 shows a cross section of the interconnection used in the second embodiment, with indication of several dimensional parameters;
- Figure 10 shows the second embodiment of the invention;
- Figure 11 shows a third embodiment of the invention.

## DETAILED DESCRIPTION OF SOME EMBODIMENTS

### First embodiment.

As a first embodiment of a device for implementing the method of the invention, given by way of non-limiting example, we have represented in Fig. 5 a device of the invention comprising an interconnection (1) having  $n = 2$  transmission conductors (11) (12) and a reference conductor (7). A transmitting circuit (5) receives at its input the  $m = 2$  “input signals of the transmitting circuit” from the  $m$  channels of the source (2). The transmitting circuit (5) comprises  $n$  output terminals which are connected to the transmission conductors (11) (12) of the interconnection (1), at the near-end of the interconnection (1). A termination circuit (4) is connected to ground and to the transmission conductors (11) (12) of the interconnection (1), at the far-end of the interconnection (1). A receiving circuit (6) is connected to the transmission conductors (11) (12) of the interconnection (1), at the far-end of the interconnection (1). The output of the receiving circuit (6) delivers  $m$  “output signals of the receiving circuit” to the destination (3). Thus, the analog or digital signals of the  $m$  channels of the source (2) are sent to the  $m$  channels of the destination (3).

The interconnection (1) is subdivided into 3 interconnection segments (103) (104) (105). The Fig. 6 shows a section of the interconnection (1) in a plane orthogonal to the direction of propagation, at a given abscissa  $z$  in any one of said interconnection segments (103) (104) (105), this cross section corresponding to a multiconductor microstrip structure. The Fig. 8 shows the same cross section, with indication of several dimensional parameters, denoted by  $s$ ,  $w$ ,  $h$  and  $t$ . In any one of said interconnection segments (103) (104) (105), the permittivity of the dielectrics does not depend on the abscissa  $z$  along the interconnection and each of said dimensional parameters takes on a fixed value. Thus, each of said interconnection segments (103) (104) (105) is such that it may be modeled, to a sufficient accuracy in a part of the frequency band used for transmission, as a  $(n + 1)$ -conductor uniform multiconductor transmission line, said multiconductor transmission line using the natural voltages referenced to ground and the natural currents as natural electrical variables.



Consequently, the interconnection (1) may be modeled, to a sufficient accuracy in said part of the frequency band used for transmission, as a  $(n + 1)$ -conductor multiconductor transmission line, said multiconductor transmission line using the natural voltages referenced to ground and the natural currents as natural electrical variables. The permittivity of the dielectrics is significantly different in the first two interconnection segments (103) (104) and also in the last two interconnection segments (104) (105). Consequently, it has not been possible to proportion the interconnection segments (103) (104) (105) such that the multiconductor transmission line used to model the whole interconnection is a uniform multiconductor transmission line. Thus, the multiconductor transmission line used to model the whole interconnection has a per-unit-length impedance matrix (denoted by  $\mathbf{Z}_G$ ) and a per-unit-length admittance matrix (denoted by  $\mathbf{Y}_G$ ) which cannot be considered as both uniform over the length of said multiconductor transmission line. However, even though the dimensional parameters  $h$  and  $t$  are not free (they are determined by the technological requirements applicable to each of said interconnection segments), the dimensional parameters  $s$  and  $w$  may easily be proportioned by a specialist, so as to obtain the same characteristic impedance matrix (denoted by  $\mathbf{Z}_{GC}$ ) for each of said interconnection segments (103) (104) (105). Thus, the characteristic impedance matrix of the multiconductor transmission line used to model the whole interconnection (1) is uniform over the length of said multiconductor transmission line.  $\mathbf{Z}_{GC}$  is given by

$$\mathbf{Z}_{GC} = \begin{pmatrix} 147 & 60 \\ 60 & 147 \end{pmatrix} \Omega \quad (20)$$

The termination circuit (4) is such that, in said part of the frequency band used for transmission, the impedance matrix, with respect to ground, of the termination circuit is a non-diagonal matrix of size  $n \times n$  approximately equal to  $\mathbf{Z}_{GC}$ .

In this first embodiment, at each abscissa  $z$  along said multiconductor transmission line, in said part of said known frequency band, there exists a non-singular matrix  $\mathbf{S}_G$  such that  $\mathbf{S}_G^{-1} \mathbf{Z}_G \mathbf{Y}_G \mathbf{S}_G$  is a diagonal matrix, said matrix  $\mathbf{S}_G$  being independent of the abscissa  $z$  along said multiconductor transmission line. Because of the symmetry of the interconnection (1), we may for instance use

$$\mathbf{S}_G = \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \quad (21)$$

which defines a differential mode and a common mode.

The transmitting circuit (5) delivers  $n$  transmission variables, each of said transmission variables being a voltage between an output terminal of the transmitting circuit (5) and ground. Each output terminal of the transmitting circuit (5) presents a low impedance with respect to

ground. Each of said transmission variables is a natural electrical variable of said  $(n + 1)$ -conductor multiconductor transmission line used to model the interconnection. Each of said transmission variables delivered by said transmitting circuit (5) is a linear combination of signals each mainly determined by one and only one of said  $m$  “input signals of the transmitting circuit”, such that the output of said transmitting circuit (5) delivers modal voltages defined by  $\mathbf{S}_G$ , each of said modal voltages being mainly determined by one and only one of said “input signals of the transmitting circuit”. Thus, the equation (17) is applicable to the operation of the transmitting circuit (5) and  $\mathbf{V}_{GM}$  produced by the transmitting circuit (5) is determined, at each point in time, by the history, up to said point in time, of said “input signals of the transmitting circuit”.

The receiving circuit (6) delivers  $m$  “output signals of the receiving circuit”, each of said “output signals of the receiving circuit” being mainly determined by one and only one of said modal voltages defined by the matrix  $\mathbf{S}_G$ . Thus, the equation (18) is applicable to the operation of the receiving circuit (6) and said “output signals of the receiving circuit” are mainly determined, at each point in time, by the history, up to said point in time, of  $\mathbf{V}_{GM}$  at the input of the receiving circuit (6).

For instance, the transmitting circuit (5) and the receiving circuit (6) may be similar to one of the transmitting circuits and receiving circuits used in the embodiments of said French patent number 0300064 and the corresponding international application, for instance to the transmitting circuit and the receiving circuit used in Fig. 7 of the French patent number 0300064 and the corresponding international application. For instance, the transmitting circuit (5) and the receiving circuit (6) may be similar to one of the transmitting circuits and receiving circuits used in the embodiments of said French patent number 0302814 and the corresponding international application.

This first embodiment is suitable for the transmission of analog signals and for the transmission of digital signals.

We note that a 2-channel link, for digital signals, using 2 transmission conductors, is described in the article of V. Stojanovic, A. Ho, B.W. Garlepp, F. Chen, J. Wei, G. Tsang, E. Alon, R.T. Kollipara, C.W. Werner, J.L. Zerbe and M.A. Horowitz entitled “Autonomous Dual-Mode (PAM2/4) Serial Link Transceiver With Adaptive Equalization and Data Recovery”, published in the journal *IEEE Journal of Solid-State Circuits*, vol. 40, No. 4, pages 1012 to 1026, in April 2005. In this paper, the two channels are referred to as “forward link” and “back channel”, respectively. However, since the link described in this paper does not use the type of termination circuit presented in the present application, echo is present in the back channel and crosstalk is high at frequencies greater than 100 MHz, so that the back channel may only be used for a reduced bandwidth signal.

Second embodiment (best mode).

As a second embodiment of a device for implementing the method of the invention, given by way of non-limiting example and best mode of carrying out the invention, we have represented in Fig. 10 a device of the invention comprising an interconnection (1) having  $n = 4$  transmission conductors (11) (12) (13) (14) and a reference conductor (7). A transmitting circuit (5) receives at its input the  $m = 4$  “input signals of the transmitting circuit” from the  $m$  channels of the source (2). The transmitting circuit (5) comprises  $n$  output terminals which are connected to the transmission conductors (11) (12) (13) (14) of the interconnection (1), at the near-end of the interconnection (1). A termination circuit (4) is connected to ground and to the transmission conductors (11) (12) (13) (14) of the interconnection (1), at the far-end of the interconnection (1). A receiving circuit (6) is connected to the transmission conductors (11) (12) (13) (14) of the interconnection (1), at the far-end of the interconnection (1). The output of the receiving circuit (6) delivers  $m$  “output signals of the receiving circuit” to the destination (3). Thus, the analog or digital signals of the  $m$  channels of the source (2) are sent to the  $m$  channels of the destination (3).

The interconnection (1) is subdivided into 2 interconnection segments (101) (102). The Fig. 7 shows a section of the interconnection (1) in a plane orthogonal to the direction of propagation, at a given abscissa  $z$  in any one of said interconnection segments (101) (102), this cross section corresponding to a multiconductor stripline structure. The Fig. 9 shows the same cross section, with indication of several dimensional parameters, denoted by  $s_1, s_2, w_1, w_2, h_1, h_2$  and  $t$ . In any one of said interconnection segments (101) (102), the permittivity of the dielectrics does not depend on the abscissa  $z$  along the interconnection and each of said dimensional parameters takes on a fixed value. Thus, each of said interconnection segments (101) (102) is such that it may be modeled, to a sufficient accuracy in a part of the frequency band used for transmission, as a  $(n + 1)$ -conductor uniform multiconductor transmission line, said multiconductor transmission line using the natural voltages referenced to ground and the natural currents as natural electrical variables.

Consequently, the interconnection (1) may be modeled, to a sufficient accuracy in said part of the frequency band used for transmission, as a  $(n + 1)$ -conductor multiconductor transmission line, said multiconductor transmission line using the natural voltages referenced to ground and the natural currents as natural electrical variables. The permittivity of the dielectrics is significantly different in the different interconnection segments (101) (102). Consequently, it has not been possible to proportion the interconnection segments (101) (102) such that the multiconductor transmission line used to model the whole interconnection is a uniform multiconductor transmission line. Thus, the multiconductor transmission line used to model the whole interconnection has a per-unit-length impedance matrix (denoted by  $\mathbf{Z}_G$ ) and

a per-unit-length admittance matrix (denoted by  $\mathbf{Y}_G$ ) which cannot be considered as both uniform over the length of said multiconductor transmission line. However, even though the dimensional parameters  $h_1$ ,  $h_2$  and  $t$  are not free in this particular design, the dimensional parameters  $s_1$ ,  $s_2$ ,  $w_1$  and  $w_2$  may easily be proportioned by a specialist, so as to obtain substantially the same characteristic impedance matrix (denoted by  $\mathbf{Z}_{GC}$ ) for each of said interconnection segments (101) (102). More precisely, the characteristic impedance matrix  $\mathbf{Z}_{GC1}$  applicable to the first segment (101) and the characteristic impedance matrix  $\mathbf{Z}_{GC2}$  applicable to the second segment (102) are such that a suitable norm of  $\mathbf{Z}_{GC1} - \mathbf{Z}_{GC2}$  is sufficiently small, so that we may for instance define  $\mathbf{Z}_{GC}$  as  $\mathbf{Z}_{GC} = (\mathbf{Z}_{GC1} + \mathbf{Z}_{GC2})/2$ . Thus, the characteristic impedance matrix of the multiconductor transmission line used to model the whole interconnection (1) is substantially uniform over the length of said multiconductor transmission line.

The termination circuit (4) is such that, in said part of the frequency band used for transmission, the impedance matrix, with respect to ground, of the termination circuit is a non-diagonal matrix of size  $n \times n$  approximately equal to  $\mathbf{Z}_{GC}$ .

Because of the multiconductor stripline structure used in this second embodiment, the interconnection (1) is such that, at each point along said multiconductor transmission line, in said part of the frequency band used for transmission, the product  $\mathbf{Z}_G \mathbf{Y}_G$  may be considered as equal to the product of a scalar and the identity matrix of order  $n$ , so that equation (15) is applicable.

This second embodiment uses voltage-mode signaling and a parallel connection to the interconnection (1), according to the Table I of said article entitled “Echo-Free and Crosstalk-Free Transmission in Particular Interconnections”. The output of the transmitting circuit (5) delivers natural voltages, each of said natural voltages being mainly determined by one and only one of said “input signals of the transmitting circuit”. Each of said “output signals of the receiving circuit” is mainly determined by one and only one of said natural voltages.

We note that, each output terminal of the transmitting circuit (5) presenting a high impedance to the interconnection (1), this second embodiment could have used a second termination circuit, at the near-end of the interconnection (1). However, only one termination circuit (4) is used in this second embodiment (as in the first embodiment) because waves coming from the interconnection (1) may only be incident on the far-end.

This second embodiment is suitable for the transmission of analog signals and for the transmission of digital signals.

In the first embodiment, we have considered an interconnection which is subdivided into 3 interconnection segments and, in the second embodiment, we have considered an interconnection which is subdivided into 2 interconnection segments. However, in both of

these embodiments, we could have considered an interconnection which is subdivided into  $p$  interconnection segments, where  $p$  is an integer greater than or equal to 2, each of said interconnection segments being such that said each of said interconnection segments may be modeled, to a sufficient accuracy in a part of the frequency band used for transmission, as a  
 5  $(n+1)$ -conductor uniform multiconductor transmission line, said multiconductor transmission line using the natural voltages referenced to ground and the natural currents as natural electrical variables.

### Third embodiment.

As a third embodiment of a device for implementing the method of the invention, given  
 10 by way of non-limiting example, we have represented in Fig. 11 a device of the invention comprising an interconnection (1) having  $n = 4$  transmission conductors and a reference conductor. The interconnection (1) cannot be modeled as a uniform multiconductor transmission line, but, taking into account the lumped impedances seen by the interconnection (1) and caused by the circuits connected to the interconnection (1) elsewhere than at the ends  
 15 of the interconnection (1), it can be modeled as a multiconductor transmission line such that the characteristic impedance matrix of said multiconductor transmission line is substantially uniform along said multiconductor transmission line. At each end of the interconnection (1), a termination circuit (4) is connected to the conductors of the interconnection (1). Two transmitting circuits (5) placed at two different abscissa  $z$  receive at their inputs the signals  
 20 from the  $m = 4$  channels of the two sources (2). Each of said transmitting circuits (5) comprises  $n$  output terminals which are connected to the transmission conductors of the interconnection (1). At three different abscissa  $z$ , a receiving circuit (6) is connected to the transmission conductors of the interconnection (1). The output of each of said receiving circuits (6) delivers  $m$  "output signals of the receiving circuit" to a destination (3).

25 In Fig. 11, each of the transmitting circuits (5) is associated with a receiving circuit (6) placed at the same abscissa  $z$  as said each of the transmitting circuits (5). Each of said transmitting circuits (5) delivers, when said each of said transmitting circuits (5) is in the activated state,  $m$  modal electrical variables, each of said modal electrical variables being mainly determined by the signal of only one channel of the source (2) connected to said each  
 30 of said transmitting circuits (5). Thus, each modal electrical variable is allocated to one and only one channel. We note that Fig. 11 shows a data bus architecture, and that the address and/or control lines needed to obtain the activated state of at most one transmitting circuit (5) at a given point in time are not shown in Fig. 11.

Each of the  $m$  "output signals of the receiving circuit" delivered by any one of the  
 35 receiving circuits (6) is mainly determined by only one of the modal voltages appearing at the

input of said any one of the receiving circuits (6). Thus, the signals of the  $m$  channels of a source (2) connected to a transmitting circuit (5) in the activated state are sent to the  $m$  channels of the destinations (3), without noticeable echo and internal crosstalk.

We note that, in the device of Fig. 11, the transmitting circuits (5) and the receiving circuits (6) being connected in parallel with the interconnection (1), they may, in order not to disturb the propagation of waves along the interconnection (1) in a detrimental way, and in order not to produce undesirable reflections at the ends of the interconnection (1), present high impedances to the interconnection (1). In the device of Fig. 11, two termination circuits (4) are necessary, because waves coming from the interconnection (1) may be incident on both ends.

This third embodiment is intended for transmitting digital signals. In Fig. 11, the bus architecture uses a direct connection of the transmitting circuits (5) and of the receiving circuits (6) to the interconnection (1). This is not a characteristic of the invention. For instance, according to the invention, one or more of the transmitting circuits (5) and/or one or more of the receiving circuits (6) may be coupled to the interconnection (1) using one or more electromagnetic couplers. This type of coupling is for instance described in the patent of the United States of America number 7,080,186 entitled "Electromagnetically-coupled bus system". This type of indirect coupling may provide a higher transmission bandwidth.

## INDICATIONS ON INDUSTRIAL APPLICATIONS

The invention is suitable for transmission between integrated circuits through an interconnection having two or more transmission conductors, the transmission presenting reduced echo and reduced internal crosstalk.

The invention has the advantage of being applicable to interconnections which cannot be modeled as a uniform multiconductor transmission line, such as, for instance, the interconnection used in Fig. 4 and discussed in the prior art section. The invention is particularly advantageous for transmission inside a rigid or flexible printed circuit assembly or inside a multi-chip module (MCM), since in this context it is often not possible to use an interconnection which can be modeled as a uniform multiconductor transmission line at the highest frequencies of operation.

The invention is particularly suitable for transmission inside an integrated circuit.

The invention is particularly suitable for multilevel signaling and for simultaneous bi-directional signaling, because such transmission schemes are more sensitive to noise than unidirectional binary signaling.

## CLAIMS

1. A method for transmitting through an interconnection (1) having  $n$  transmission conductors and a reference conductor,  $n$  being an integer greater than or equal to 2, said method providing, in a known frequency band,  $m$  transmission channels each corresponding to a signal to be sent  
5 from the input of at least one transmitting circuit (5) to the output of at least one receiving circuit (6), where  $m$  is an integer greater than or equal to 2 and less than or equal to  $n$ , said method comprising the steps of:  
modeling the interconnection (1) in a part of said known frequency band, taking into account  
the lumped impedances seen by the interconnection (1) and caused by the circuits  
10 connected to the interconnection (1) elsewhere than at the ends of the interconnection (1), as a  $(n + 1)$ -conductor multiconductor transmission line, said multiconductor transmission line using natural voltages referenced to ground and natural currents as natural electrical variables, said multiconductor transmission line having a per-unit-length impedance matrix and a per-unit-length admittance matrix which are not both  
15 uniform or substantially uniform over the length of said multiconductor transmission line, the characteristic impedance matrix of said multiconductor transmission line being substantially uniform over the length of said multiconductor transmission line;  
coupling the terminals of at least one termination circuit (4) to said reference conductor and to each of said transmission conductors, said at least one termination circuit (4) being,  
20 in said part of said known frequency band, approximately characterized, for said interconnection (1), by an impedance matrix with respect to ground, said impedance matrix with respect to ground being a matrix of size  $n \times n$ .
2. The method of claim 1, wherein, in said part of said known frequency band, said impedance matrix with respect to ground is a non-diagonal matrix substantially equal to said characteristic  
25 impedance matrix.
3. The method of any of the claims 1 or 2, wherein, at each point along said multiconductor transmission line, in said part of said known frequency band, there exists an invertible matrix, denoted by  $\mathbf{S}$ , such that the inverse of  $\mathbf{S}$  times said per-unit-length impedance matrix times said per-unit-length admittance matrix times  $\mathbf{S}$  is substantially a diagonal matrix, said matrix  $\mathbf{S}$   
30 being substantially uniform over the length of said multiconductor transmission line.

4. The method of claim 3, further comprising the steps of:

using one said transmitting circuit (5) receiving  $m$  “input signals of the transmitting circuit” corresponding each to a transmission channel, the output of said transmitting circuit (5) being coupled to the  $n$  transmission conductors, the output of said transmitting circuit (5) delivering modal electrical variables defined by a transition matrix from modal electrical variables to natural electrical variables, said transition matrix from modal electrical variables to natural electrical variables being equal to said matrix  $\mathbf{S}$  or to the inverse of the transpose of said matrix  $\mathbf{S}$ , each of said modal electrical variables being mainly determined by one and only one of said “input signals of the transmitting circuit”; and

using one said receiving circuit (6) delivering  $m$  “output signals of the receiving circuit” corresponding each to a transmission channel, the input of said receiving circuit (6) being coupled to the  $n$  transmission conductors, each of said “output signals of the receiving circuit” being mainly determined by one and only one of said modal electrical variables defined by said transition matrix from modal electrical variables to natural electrical variables.

5. The method of any of the claims 1 or 2, wherein, at each point along said multiconductor transmission line, in said part of said known frequency band, the product of said per-unit-length impedance matrix and said per-unit-length admittance matrix is substantially equal to the product of a scalar and the identity matrix of order  $n$ .

6. The method of claim 5, further comprising the steps of:

using one said transmitting circuit (5) receiving  $m$  “input signals of the transmitting circuit” corresponding each to a transmission channel, the output of said transmitting circuit (5) being coupled to at least  $m$  of said transmission conductors, the output of said transmitting circuit (5) delivering natural electrical variables, each of said natural electrical variables being mainly determined by one and only one of said “input signals of the transmitting circuit”; and

using one said receiving circuit (6) delivering  $m$  “output signals of the receiving circuit” corresponding each to a transmission channel, the input of said receiving circuit (6) being coupled to at least  $m$  of said transmission conductors, each of said “output signals of the receiving circuit” being mainly determined by said natural electrical variables.



7. A device for transmission providing, in a known frequency band,  $m$  transmission channels each corresponding to a signal to be sent from the input of at least one transmitting circuit (5) to the output of at least one receiving circuit (6), where  $m$  is an integer greater than or equal to 2, comprising:

- 5 an interconnection (1) having  $n$  transmission conductors and a reference conductor,  $n$  being an integer greater than or equal to  $m$ , the interconnection (1) being modeled, in a part of said known frequency band, taking into account the lumped impedances seen by the interconnection (1) and caused by the circuits connected to the interconnection (1) elsewhere than at the ends of the interconnection (1), as a  $(n + 1)$ -conductor  
 10 multiconductor transmission line, said multiconductor transmission line using the natural voltages referenced to ground and the natural currents as natural electrical variables, said multiconductor transmission line having a per-unit-length impedance matrix and a per-unit-length admittance matrix which are not both uniform or substantially uniform over the length of said multiconductor transmission line, the  
 15 characteristic impedance matrix of said multiconductor transmission line being substantially uniform over the length of said multiconductor transmission line;  
 at least one termination circuit (4) coupled to the reference conductor and to each of said transmission conductors, said at least one termination circuit (4) being, when said at least one termination circuit (4) is in the activated state, approximately characterized,  
 20 for said interconnection (1), at at least one quiescent operating point, for small signals in said part of said known frequency band, by an impedance matrix with respect to ground, said impedance matrix with respect to ground being a non-diagonal matrix of size  $n \times n$  substantially equal to said characteristic impedance matrix.

8. The device of claim 7, wherein, at each point along said multiconductor transmission line,  
 25 in said part of said known frequency band, there exists an invertible matrix, denoted by  $\mathbf{S}$ , such that the inverse of  $\mathbf{S}$  times said per-unit-length impedance matrix times said per-unit-length admittance matrix times  $\mathbf{S}$  is substantially a diagonal matrix, said matrix  $\mathbf{S}$  being substantially uniform over the length of said multiconductor transmission line, said device further comprising:

- 30 at least one said transmitting circuit (5) receiving  $m$  “input signals of the transmitting circuit” corresponding each to a transmission channel, the output of said at least one said transmitting circuit (5) being coupled to the  $n$  transmission conductors, the output of said at least one said transmitting circuit (5) delivering modal electrical variables when said at least one said transmitting circuit (5) is in the activated state, said modal  
 35 electrical variables being defined by a transition matrix from modal electrical variables

to natural electrical variables, said transition matrix from modal electrical variables to natural electrical variables being equal to said matrix  $\mathbf{S}$  or to the inverse of the transpose of said matrix  $\mathbf{S}$ , each of said modal electrical variables being mainly determined by one and only one of said “input signals of the transmitting circuit”; and

5 at least one said receiving circuit (6) delivering, when said at least one said receiving circuit (6) is in the activated state,  $m$  “output signals of the receiving circuit” corresponding each to a transmission channel, the input of said at least one said receiving circuit (6) being coupled to the  $n$  transmission conductors, each of said “output signals of the receiving circuit” being mainly determined by one and only one of said modal

10 electrical variables defined by said transition matrix from modal electrical variables to natural electrical variables.

9. The device of claim 7, wherein, at each point along said multiconductor transmission line, in said part of said known frequency band, the product of said per-unit-length impedance matrix and said per-unit-length admittance matrix is substantially equal to the product of a

15 scalar and the identity matrix of order  $n$ , said device further comprising:

at least one said transmitting circuit (5) receiving  $m$  “input signals of the transmitting circuit” corresponding each to a transmission channel, the output of said at least one said transmitting circuit (5) being coupled to at least  $m$  of said transmission conductors, the output of said at least one said transmitting circuit (5) delivering natural electrical

20 variables when said at least one said transmitting circuit (5) is in the activated state, each of said natural electrical variables being mainly determined by one and only one of said “input signals of the transmitting circuit”; and

at least one said receiving circuit (6) delivering, when said at least one said receiving circuit (6) is in the activated state,  $m$  “output signals of the receiving circuit” corresponding

25 each to a transmission channel, the input of said at least one said receiving circuit (6) being coupled to at least  $m$  of said transmission conductors, each of said “output signals of the receiving circuit” being mainly determined by one and only one of said natural electrical variables.

10. The device of any of the claims 7 to 9, wherein the number  $m$  of transmission channels

30 between one of said transmitting circuits (5) and one of said receiving circuits (6) is equal to the number  $n$  of transmission conductors.

11. The device of any of the claims 7 to 10, wherein each of said termination circuits (4) is arranged at an end of said interconnection (1).

12. The device of any of the claims 7 to 11, wherein said interconnection (1) is subdivided into  $p$  interconnection segments, where  $p$  is an integer greater than or equal to 2, each of said interconnection segments being such that said each of said interconnection segments may be modeled, to a sufficient accuracy in a part of the frequency band used for transmission, as a
- 5  $(n+1)$ -conductor uniform multiconductor transmission line, said multiconductor transmission line using the natural voltages referenced to ground and the natural currents as natural electrical variables.

## ABSTRACT

### **Method for transmission using a non-uniform interconnection.**

5 The invention relates to a method and a device for transmission through interconnections used for sending a plurality of electrical signals.

10 An interconnection (1) having 4 transmission conductors and a reference conductor cannot be modeled as a uniform multiconductor transmission line. Each end of the interconnection (1) is connected to a termination circuit (4). The transmitting circuits (5) receive at their inputs the signals from the 4 channels of the two sources (2), and are connected to the interconnection (1). A transmitting circuit (5) in the activated state produces modal electrical variables, each modal electrical variable being allocated to one and only one channel. The receiving circuits (6) are connected to the interconnection (1), each receiving circuit (6) being such that the signals of the 4 channels of a source (2) connected to a transmitting circuit (5) in the activated state are sent to the four channels of the destinations (3), without noticeable  
15 echo and internal crosstalk.

Figure for the abstract: Figure 11.

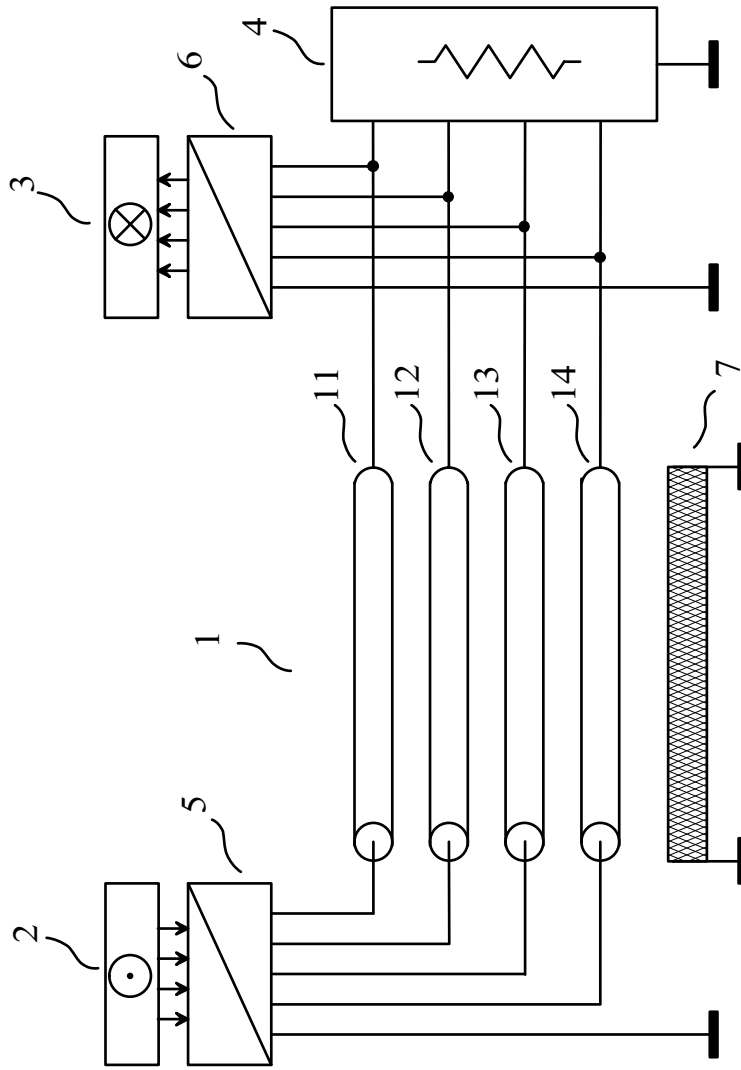
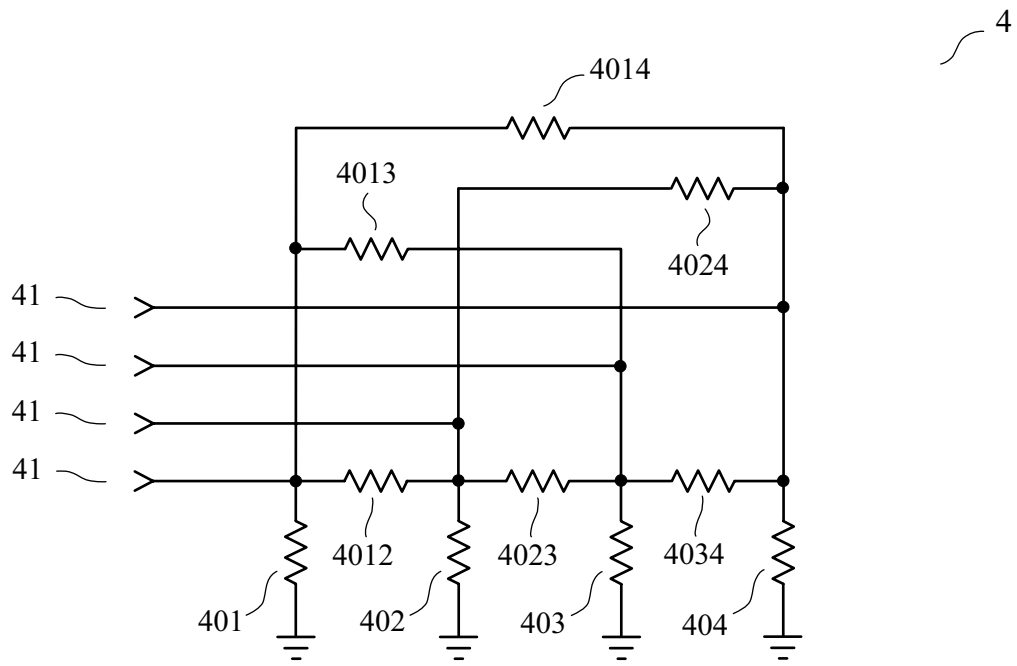
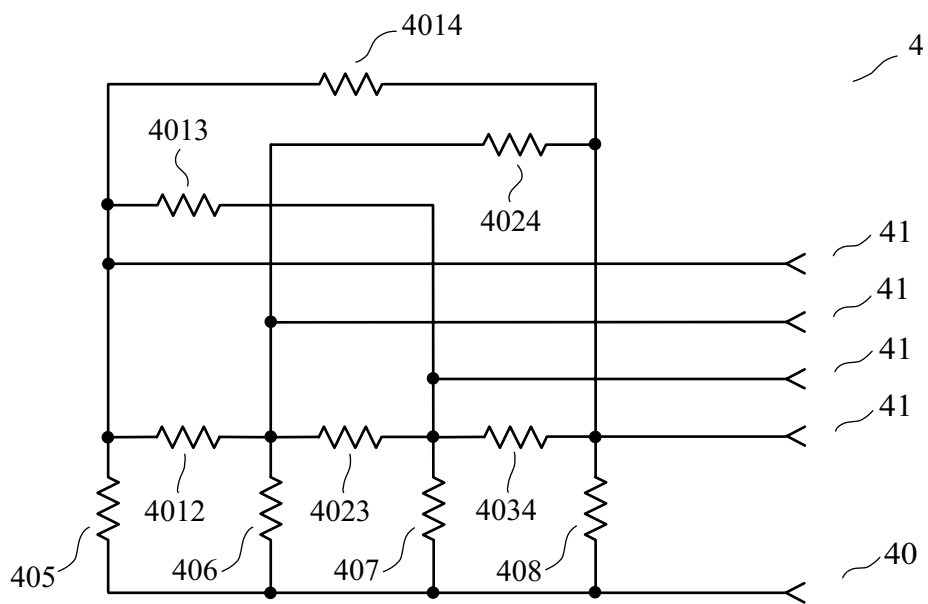


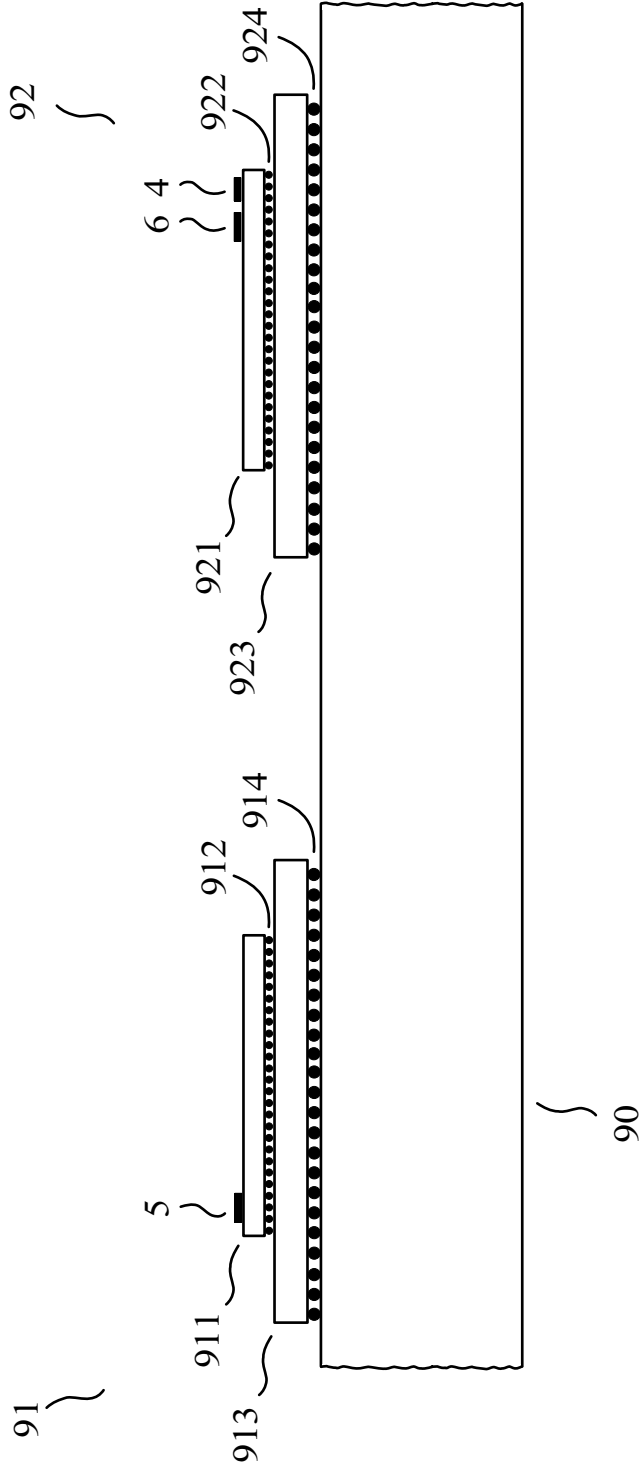
FIG. 1



**FIG. 2**



**FIG. 3**



**FIG. 4**

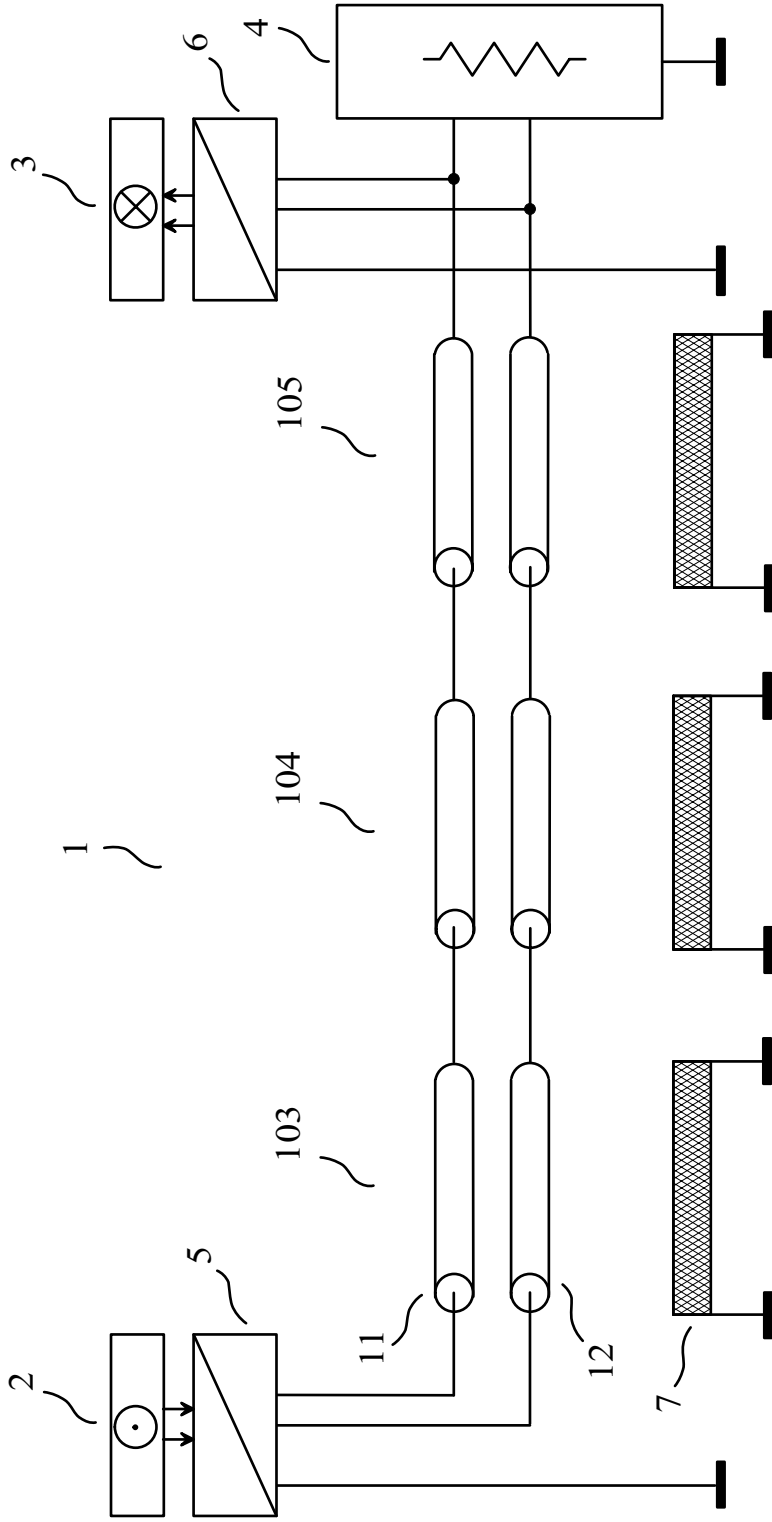
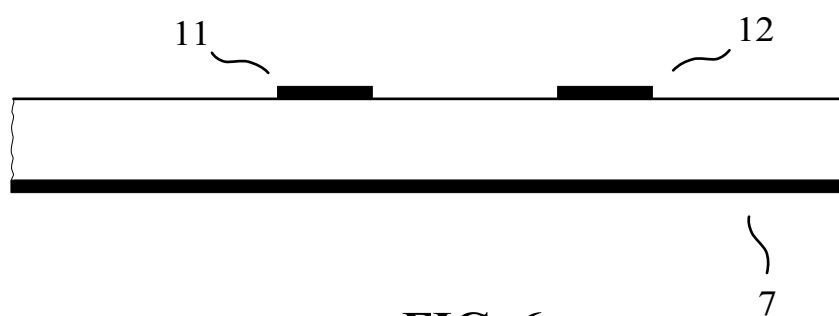
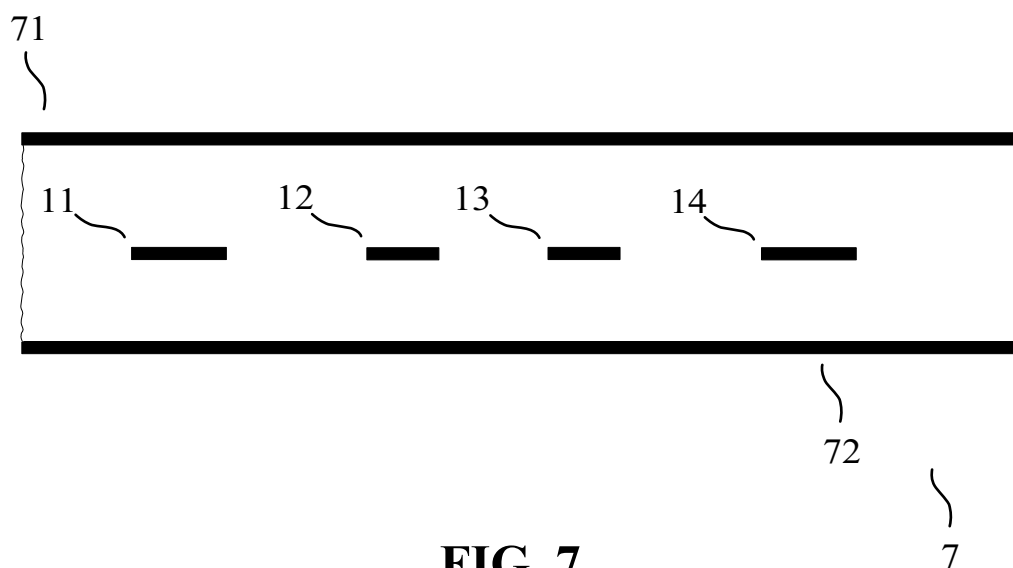


FIG. 5





**FIG. 6**



**FIG. 7**

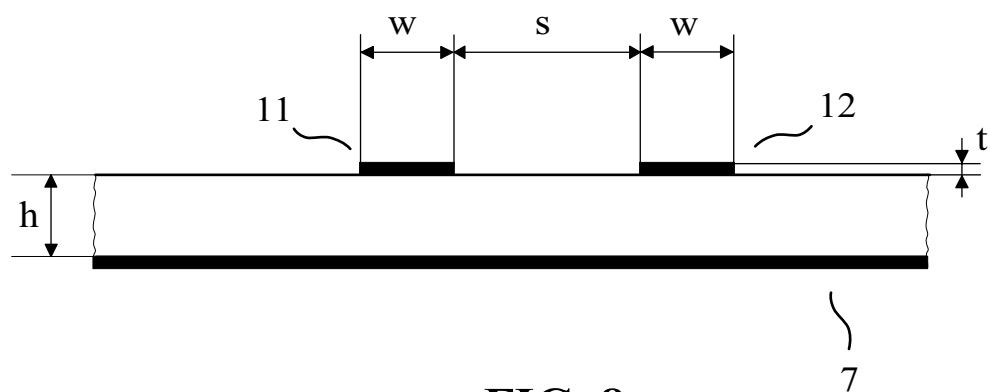


FIG. 8

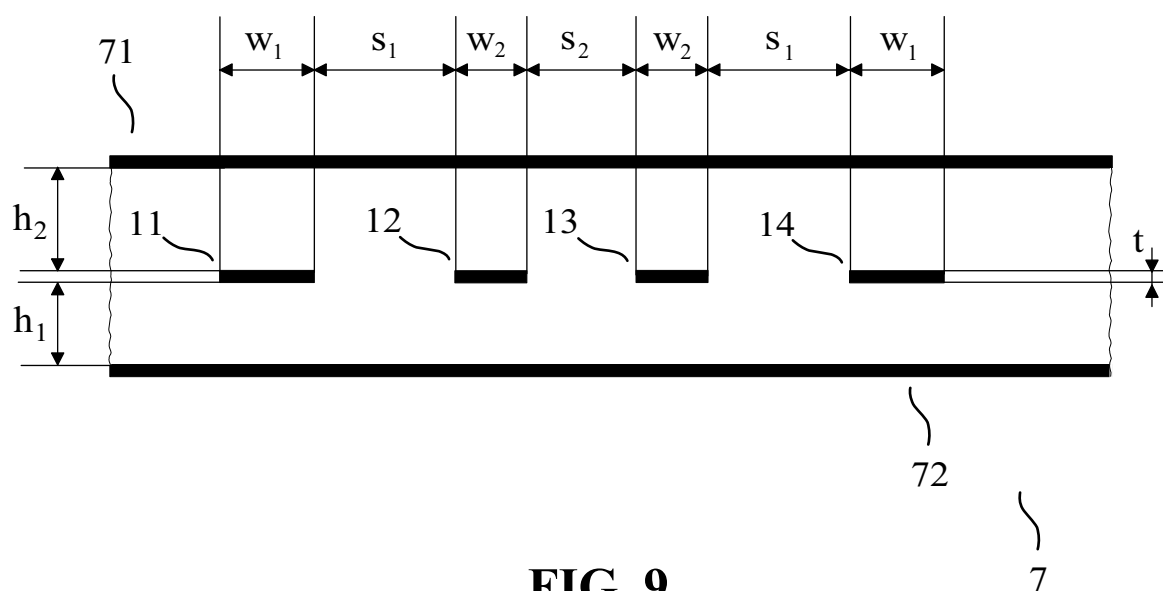


FIG. 9

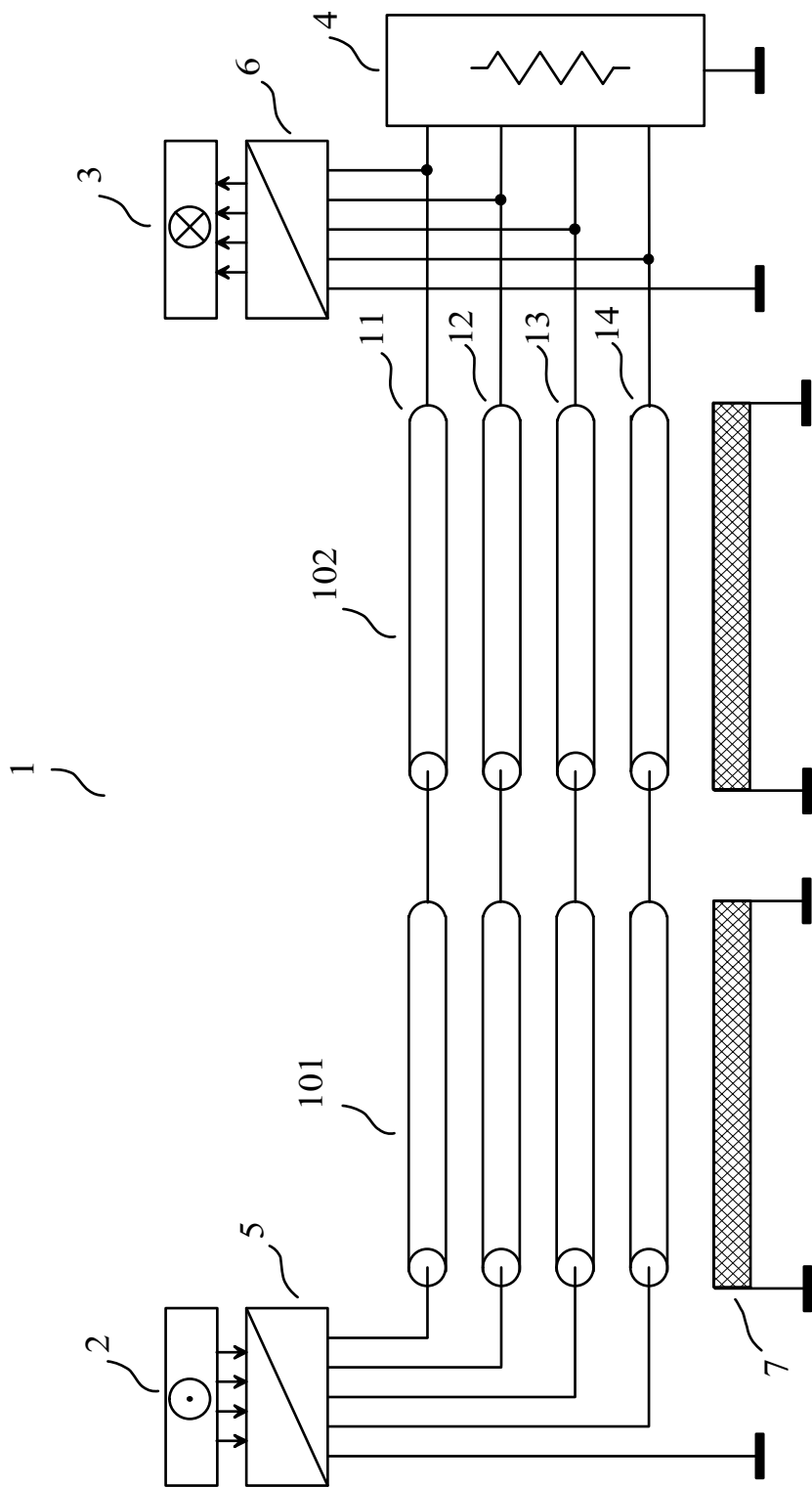


FIG. 10

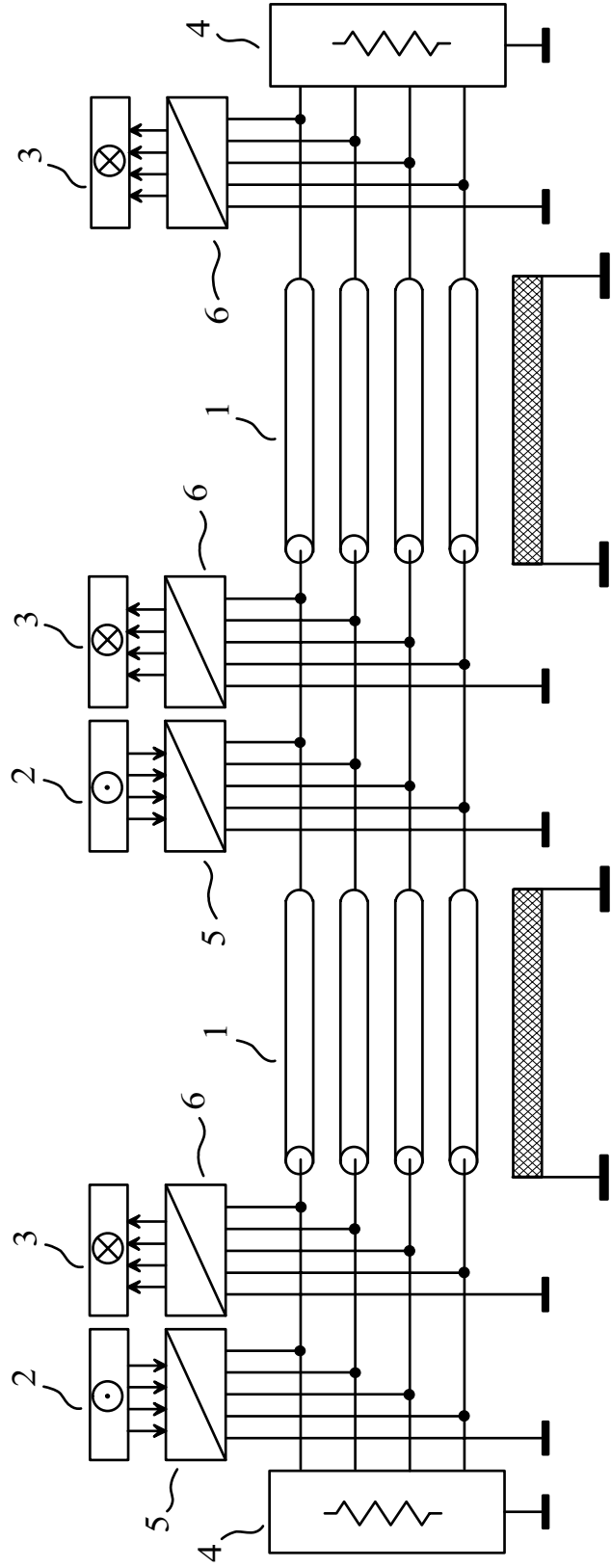


FIG. 11