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(54) TRANSMISSION OF SIGNALS ON MULTI-LAYER SUBSTRATES WITH MINIMUM INTERFERENCE

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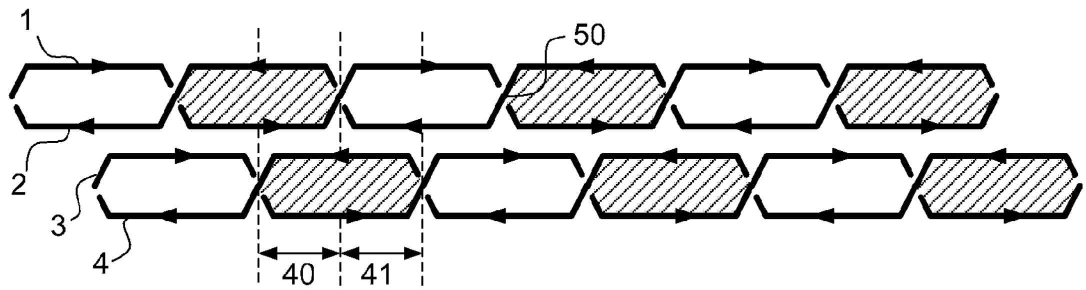
(57) **ABSTRACT**

A signal transmission system including first and second transmission lines laid out side by side on a planar surface over a length L, each transmission line including a first conducting path and a second conducting path and each transmission line including a plurality of crossover structures at each of which the first and second conducting paths of that transmission line cross over each other to reverse the position of the two conducting paths relative to each other, wherein the plurality of crossover structures on the two transmission lines are arranged over the length L of the two transmission lines such that each of the first and second conducting paths of the first transmission line is a nearest neighbor of each of the first and second conducting paths of the second transmission line over distances that are substantially the same.



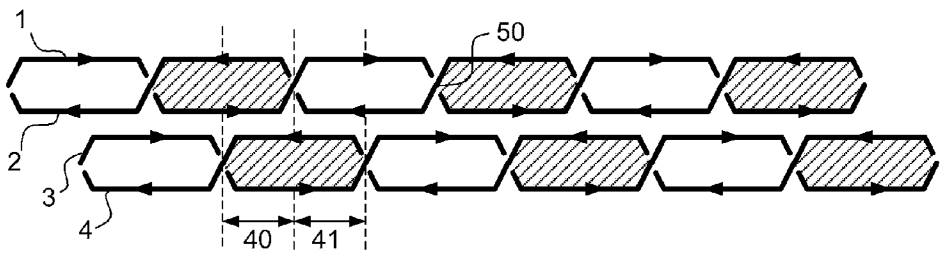



FIG. 1

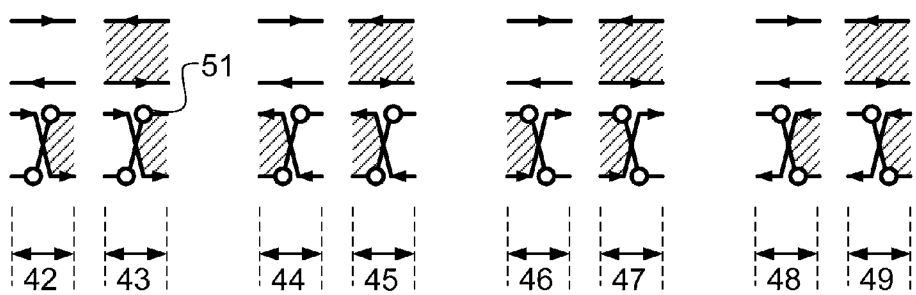



FIG. 2

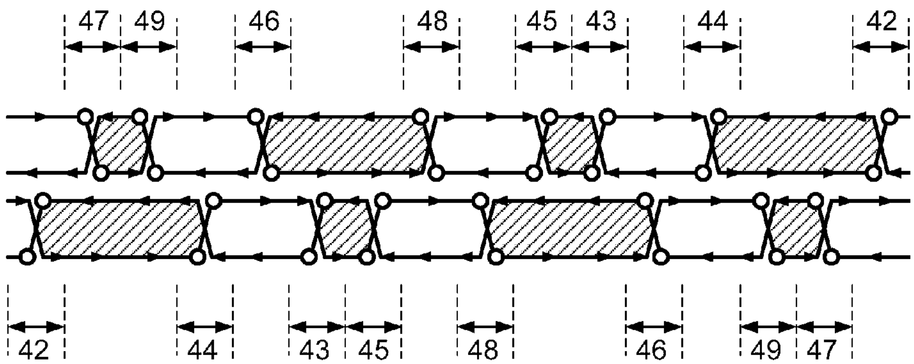



FIG. 3

# TRANSMISSION OF SIGNALS ON MULTI-LAYER SUBSTRATES WITH MINIMUM INTERFERENCE

**[0001]** This application claims the benefit under 35 U.S.C. §119(e) of Provisional Application Serial No. 62/015,604 filed Jun. 23, 2014, entitled "Method for Transmission and Coupling of Signals on Multi-Layer Boards with Minimum Interference," the entire contents of which are incorporated herein by reference.

## TECHNICAL FIELD

**[0002]** The described inventions generally relate to high frequency signal distribution on Printed Circuits Boards (PCBs) and other multi-layer substrates so as to preserve signal integrity in the presence of line cross coupling.

## BACKGROUND OF THE INVENTION

**[0003]** High frequency signal transmission is most commonly point-to-point. Power is generated at a source (the transmitter), and delivered to a load (the receiver) via a transmission line. In such cases, the receiver usually includes a terminating resistance that is equal to the characteristic impedance of the transmission line. The transmitted signal power is dissipated in this resistance, and no signal reflection occurs from the receiver.

**[0004]** Complex systems may comprise multiple distribution lines of the above type. In such systems, any signal coupled between the lines is a source of interference.

## SUMMARY

**[0005]** The embodiments described herein employ a method for distributing two or more differential signal transmission lines in planar technologies such as PCBs. The transmission lines are arranged in such a way as to have balanced opposing regions of mutual coupling, resulting in minimal net coupling for lines in physical proximity.

**[0006]** In general, in one aspect, the invention features a signal transmission system including first and second transmission lines laid out side by side on a planar surface over a length L, each transmission line including a first conducting path and a second conducting path and each transmission line including a plurality of crossover structures at each of which the first and second conducting paths of that transmission line cross over each other to reverse the position of the two conducting paths relative to each other, wherein the plurality of crossover structures on the two transmission lines are arranged over the length L of the two transmission lines such that each of the first and second conducting paths of the first transmission line is a nearest neighbor of each of the first and second conducting paths of the second transmission line over distances that are substantially the same.

**[0007]** Other embodiments may include one or more of the following features. The plurality of crossover structures on the two transmission lines are arranged over the length L of the two transmission lines such that each of the first and second conducting paths of the first transmission line is a nearest neighbor of each of the first and second conducting paths of the second transmission line over distances that are equal. The distance over which each conducting path of the first transmission line is a nearest neighbor of a conducting path of the second transmission lines is equal to L/4. The signal transmission system also includes a substrate defining the planar surface. The first and second transmission lines are differential transmission lines. The plurality of crossover structures on the first transmission line are staggered relative to the plurality of crossover structures on the second transmission line. Each crossover structure of the plurality of crossover structures on the first and second transmission lines includes an in-plane crossover and an out-of-plane crossover. The out-of-plane crossover has two vertical, electrically conductive structures to transition to and from a conductive path located in a plane that is either above or below the planar surface. Each of the two electrically conducive structures includes an electrically conductive via. The plurality of crossover structures in the first transmission line are constructed such that the first conducting path of the first transmission line has an equal number of in-plane crossovers and out-of-plane crossovers. The plurality of crossover structures in the first transmission line are constructed such that the second conducting path of the first transmission line has an equal number of in-plane crossovers and out-of-plane crossovers. The plurality of crossover structures in the second transmission line are constructed such that the first conducting path of the second transmission line has an equal number of in-plane crossovers and out-of-plane crossovers. The plurality of crossover structures in the second transmission line are constructed such that the second conducting path of the second transmission line has an equal number of in-plane crossovers and out-of-plane crossovers. The first and second transmission lines are designed to carry signals having a wavelength λ and wherein distances between crossover structures in each transmission line are shorter than **214**. The signal transmission system also includes an integrated circuit wherein the first and second transmission lines are fabricated within the integrated circuit.

**[0008]** The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0009]** FIG. **1** shows a layout of two transmission lines using multiple crossovers.

**[0010]** FIG. **2** shows multiple different crossover structures for use in multi-layer planar technologies.

**[0011]** FIG. **3** shows a sequence of line sections formed by multiple crossover structures in two parallel transmission lines.

## DETAILED DESCRIPTION

**[0012]** A common technique for minimizing the electromagnetic coupling between different transmission lines is to form a shielded enclosure by surrounding each of the lines with a conductor. Additionally, coupling can generally be reduced by increasing the physical distance between the lines. In applications where the use of these techniques is not feasible or is undesirable, an alternative technique, described herein, can be applied.

**[0013]** A method that can be employed in planar technologies such as PCBs or multi-layer ICs is shown in FIG. **1**. In this diagram, four conducting lines **1-4** are formed into two differential lines, one line consisting of the pair **1-2** and the other consisting of the pair **3-4**. When placed in proximity, mutual electromagnetic coupling will occur between these two pairs of lines, determined by their proximity to each other and by the physical length of the region of interaction. Within a particular differential transmission line, the current flow (indicated by arrows) in the pair of conducting lines at any position along the line is substantially equal in magnitude but opposite in direction. (The actual direction of current flow alternates with time and location, so the diagram in FIG. **1** may be considered to represent the configuration at an instant in time.)

**[0014]** If, as shown in FIG. **1**, crossover structures **50** are provided, the positions of the two conducting lines in the differential pair are swapped at those crossover structures to reverse their positions relative to each other. The result, as shown in the diagram, is to make alternating regions of clockwise and counter-clockwise current flow, shown as unshaded and shaded regions, respectively. This results in a reversal of both the electric and magnetic field distribution emanating from the lines, and consequently a change in sign of the electromagnetic coupling between the two pairs.

**[0015]** Electromagnetic coupling between uniform transmission lines accrues on a per-unit-length basis. FIG. **1** shows one such interval **40** in which electrical coupling may occur. Similarly, coupling will occur in the interval **41**. However, by a suitable arrangement of the conductors and choice of the interval lengths, the coupling in interval **41** may nearly cancel that in interval **40**, resulting in a significant reduction in net coupling. The most obvious arrangement, as suggested by the figure, is the one in which the physical structures in intervals **40** and **41** have mirror symmetry and consequently the same magnitude of coupling per unit length. However, because of the crossover structure in one of the conducting pairs, the polarity is switched, resulting in a change in sign of the coupling. In a regular structure this pattern can be repeated. However, it is not strictly necessary to use a regular pattern. The basic principle is the local cancellation of accrued coupling by the use of the crossover structure to change the polarity.

**[0016]** In finite frequency applications, it is not generally possible to achieve perfect cancellation using this method because the signals propagate at finite speed in the transmission lines. Consequently, the coupling in the two intervals **40** and **41** will differ by some phase, making their cancellation imperfect. However, if the distance between the intervals is short compared with the signal wavelength, significant reduction in coupling may be achieved by using this method.

**[0017]** The crossover structure is formed by two crossovers, an in-plane line crossover and an out-of-plane line crossover. The in-plane line crossover is formed by a line that jogs over within the plane on which the conductor lines are formed. To implement the out-of-plane line crossover in multi-layer planar technologies it is necessary to make vertical transitions in one of the lines so that it passes over or under the other line. Thus, the crossover section of the line is formed in a different plane. The out-of-plane crossovers are shown in FIG. **2** in which vertical connecting conducting thru-vias **51** are indicated by the small circles. Especially in PCB technologies where the dielectric thickness may be comparable to the signal line cross-sectional dimensions, the vertical transition and crossing line structure form a half-loop that may generate a significant component of lateral electromagnetic field coupling to the adjacent line. This creates an added source of coupling that can be cancelled using the same principle of polarity reversal.

**[0018]** FIG. **2** shows an example interval **42** consisting of a crossover structure adjacent to a pair of lines. This structure is paired with the structure in interval **43** which is identical except for the reversal in polarity of the upper differential lines. Because of this polarity reversal and the symmetry of their structures, the coupling in these two intervals, except for the phase shift mentioned above, will cancel. Similarly, coupling cancellation is obtained in intervals **44** and **45**, **46** and **47**, and **48** and **49**.

**[0019]** The sections shown in FIG. **2** represent the eight possible combinations (four different types of crossover structure and two different polarities). These sections may be combined sequentially to form a transmitting structure with minimal mutual coupling. FIG. **3** shows an example of a sequence of **16** line sections. In this sequence there are eight crossover structures in the bottom transmission line and eight in the top. The crossover structures in the bottom line are implemented from one each of the eight structures shown in FIG. **2**. Consequently, coupling that may occur from any one of these sections is approximately cancelled by coupling of opposite sign in one of the others. The crossover structures in the top line are similarly implemented, using rotated sections to place the crossover in the upper line.

**[0020]** Note that the crossover structures are staggered, i.e., they are not next to each other. There's nothing that prohibits one from placing crossovers in the two adjacent transmission lines next to each, but doing so would not do anything to reduce the coupling between the two lines. If two crossover structures are adjacent, both lines flip, so there is no net change in the sign of the coupling.

**[0021]** The particular sequence shown in FIG. **3** is only one example of a large number of possible sequences. With reference to FIG. **2** it can be seen, for example, that the section **42** can be exchanged with section **48** without changing the connectivity, section **43** with **49**, etc.

**[0022]** Another consideration for the crossover structures in PCB technologies is the signal path length. In differential transmission lines using cross-over structures as shown in FIG. **6**, the line passing through the vertical transition is longer than the line that does not, unless some other compensating design feature is added. This difference in length causes added delay in the longer line, and can cause undesirable timing skew in a differential transmission line. The overall sequence of sections shown in FIG. **3** has an equal number of vertical transitions for all four of the lines to avoid this. This is true of all sequences that use the eight basic structures in both lines.

**[0023]** In line structures having regular line-to-line separations, a general condition for cancellation is that the length of the intervals intended to cancel each other be the same in a pair-wise fashion. However, it is not necessary for all intervals in the overall structure to be the same. In an arrangement like the one shown in FIG. **2**, it may be desirable to make all of the intervals and all of the crossover structures the same, since this facilitates design and analysis, but it is not strictly necessary. Also note that a regular structure, like the one shown in FIG. **3**, can be repeated indefinitely to form long sections of lines having minimal mutual electrical coupling. Other regular structures and even irregular structures can be devised based on the same concept of cancellation through polarity reversal.

**[0024]** The coupling between the two differential transmission lines is electromagnetic—i.e., it depends on both electric fields (arising from voltages) and magnetic fields (arising from currents). In a transmission line, the voltage and current are linearly related by the characteristic impedance. Coupling is similarly related and is linked to both types of fields. In a differential line, the currents in the two conductors are of equal magnitude but run in opposite directions and the voltages along the lines are of equal magnitude but of opposite signs. So, a possibly more useful way to think of the coupling between the two transmission lines is that the proximity component is the same on either side of the crossover, but both magnetic and electric fields have flipped signs. Thus, net coupling per unit length on one side of the coupler structure is of equal magnitude but opposite sign to coupling on the other side.

**[0025]** Notice that the crossover structures on the two transmission lines are arranged over a length L of the two transmission lines such that each of the conducting paths of the first transmission line is a nearest neighbor of each of the conducting paths of the second transmission line over distances that are equal or approximately equal. (It is approximate because the crossovers are discrete structures that are separated by finite distances.) In other words, the distance over which the various combinations of conducting paths are nearest neighbors is equal to or approximately equal to L/4.

**[0026]** The transmission lines that are described herein are differential. One important characteristic of differential lines is that the two conducting lines that form the pair need to be balanced. The most convenient way to achieve balance is to take advantage of symmetry. In the examples that are illustrated, the number of times a conductor crosses over out-of-plane is equal to the number of times it crosses in-plane, so the same is true of the other conductor in the pair. This symmetry maintains balance. For the arrangement involving two pairs, it is also important for both differential lines in the pair to have identical transmission characteristics. So the symmetry of the arrangement guarantees this as well. That's why the number and type of crossover structures is the same for all four of the conductors.

**[0027]** So, as one moves along the two transmission lines counting the total number of crossover structures in each line, the total number of crossover structures on one line is always approximately equal to the total number of crossover structures on the other line. The equality is approximate because the crossover structures are staggered, so as one moves along the two lines the count of crossover structures in one line will increase while the count in the other line remains the same—so the count in the two lines is not necessarily equal depending on where you are on the line. But as one moves further along the lines, the count in both lines will become equal again as crossover structures are encountered in the other line. In other words, the crossover structures are roughly equally distributed along both lines.

**[0028]** In addition, in each transmission line, the number of out-of-plane crossovers along one conducting path is equal to the number of out-of-plane crossovers along the other conducting path. This guarantees that the actual lengths of the two conducting lines are equal.

**[0029]** At 1 GHz the wavelength of a signal is about six inches. Generally, the crossovers need to be inserted an intervals small compared with one quarter wavelength, which would be 1.5 inches. So, crossovers at half-inch intervals is a reasonable choice, though larger or smaller intervals could also be used. Furthermore, at higher or lower frequencies the intervals could be proportionally smaller or larger.

**[0030]** The technology described herein has particular applicability to multi-point signal generation networks and low cost antenna arrays such as those described in U.S. Pat. No. 8,259,884 and U.S. Pat. No. 8,611,959, respectively, the contents of which are incorporated herein in their entirety. For example, referring to FIG. **5** in that '884 patent, there is shown two tree-networks, one of which carries a first carrier signal and the second of which carries a second carrier signal. At various places the branch of one tree network runs alongside (e.g. "parallel") to a corresponding branch of the other tree network. For that pair of branches, one carries the first carrier signal in one direction and the other branch carries the second carrier signal in the other direction. Along the length of the dual parallel transmission lines, there are number of Arrival-Time-Averaging Circuits (ATACs), each with one input connect to one of the transmission lines and a second input connected to the other transmission line. Those parallel transmission lines can be laid out using the concepts described herein to reduce interference that one line causes in the other.

**[0031]** Other embodiments are within the following claims.

What is claimed is:

**1**. A signal transmission system comprising first and second transmission lines laid out side by side on a planar surface over a length L, each transmission line comprising a first conducting path and a second conducting path and each transmission line comprising a plurality of crossover structures at each of which the first and second conducting paths of that transmission line cross over each other to reverse the position of the two conducting paths relative to each other,

wherein the plurality of crossover structures on the two transmission lines are arranged over the length L of the two transmission lines such that each of the first and second conducting paths of the first transmission line is a nearest neighbor of each of the first and second conducting paths of the second transmission line over distances that are substantially the same.

**2**. The signal transmission system of claim **1**, wherein the plurality of crossover structures on the two transmission lines are arranged over the length L of the two transmission lines such that each of the first and second conducting paths of the first transmission line is a nearest neighbor of each of the first and second conducting paths of the second transmission line over distances that are equal.

**3**. The signal transmission system of claim **1**, wherein the distance over which each conducting path of the first transmission line is a nearest neighbor of a conducting path of the second transmission lines is equal to L/4.

**4**. The signal transmission system of claim **1**, further comprising a substrate defining said planar surface.

**5**. The signal transmission system of claim **1**, wherein the first and second transmission lines are differential transmission lines.

**6**. The signal transmission system of claim **1**, wherein the plurality of crossover structures on the first transmission line are staggered relative to the plurality of crossover structures on the second transmission line.

**7**. The signal transmission system of claim **1**, wherein each crossover structure of the plurality of crossover structures on the first and second transmission lines comprises an in-plane crossover and an out-of-plane crossover.

**8**. The signal transmission system of claim **7**, wherein the out-of-plane crossover has two vertical, electrically conductive structures to transition to and from a conductive path located in a plane that is either above or below the planar surface.

**9**. The signal transmission system of claim **8**, wherein each of the two electrically conducive structures comprises an electrically conductive via.

**10**. The signal transmission system of claim **7**, wherein the plurality of crossover structures in the first transmission line are constructed such that the first conducting path of the first transmission line has an equal number of in-plane crossovers and out-of-plane crossovers.

**11**. The signal transmission system of claim **10**, wherein the plurality of crossover structures in the first transmission line are constructed such that the second conducting path of the first transmission line has an equal number of in-plane crossovers and out-of-plane crossovers.

**12**. The signal transmission system of claim **11**, wherein the plurality of crossover structures in the second transmission line are constructed such that the first conducting path of the second transmission line has an equal number of in-plane crossovers and out-of-plane crossovers.

**13**. The signal transmission system of claim **12**, wherein the plurality of crossover structures in the second transmission line are constructed such that the second conducting path of the second transmission line has an equal number of in-plane crossovers and out-of-plane crossovers.

**14**. The signal transmission system of claim **1**, wherein the first and second transmission lines are designed to carry signals having a wavelength and wherein distances between crossover structures in each transmission line are shorter than L/4.

**15**. The signal transmission system of claim **1**, further comprising an integrated circuit wherein the first and second transmission lines are fabricated within the integrated circuit.

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