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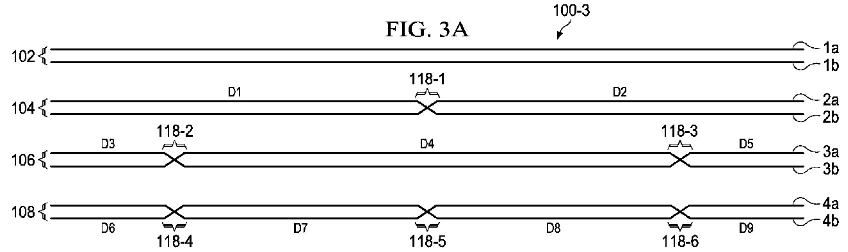
(54) **Title**: CROSS-TALK REDUCTION USING ORTHOGONAL COUPLING

FIG. 3A



(57) **Abstract**: A plurality of pairs of differential transmission lines (102, 104, 106, 108) includes a set of pairs of differential transmission lines (104, 106, 108) with each pair of differential transmission lines from the set of pairs of differential transmission lines including at least one twist (118-1 to 118-6) to alternate current direction. The twists (118-1 to 118-6) of the differential transmission lines (104, 106, 108) are arranged at distance locations (D1 to D9) such that alternating current directions substantially eliminate cross-talk across the plurality of pairs of differential transmission lines (102, 104, 106, 108).

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CROSS-TALK REDUCTION USING ORTHOGONAL COUPLING

[0001] This relates generally to communication over differential lines and, more particularly, to reducing cross-talk over differential lines.

BACKGROUND

[0002] As on-chip density increases, as distances shrink, and as speeds increase, cross-talk between communication lines has become an ever-increasing problem. Cross-talk, however, is a well-known problem that has been examined for many years, creating several solutions. Examples of these solutions are the use of shielding, microstrips, and multi-mode transmission line theory, but each solution has drawbacks, which means that each is ill-suited for use in high-density on-chip communication lines. Therefore, there is a need for a way to reduce cross-talk.

[0003] An example of a conventional arrangement is given in Mensink et al., "Optimally-Placed Twists in Global On-Chip Differential Interconnects," Proc. of ESSCIRC, Grenoble, France, 2005, pp. 475-478.

SUMMARY

[0004] An example embodiment provides an apparatus comprising a plurality of pairs of differential transmission lines, wherein the plurality of pairs of differential transmission lines includes a set of pairs of differential transmission lines with each pair of differential transmission lines from the set of pairs of differential transmission lines including at least one twist to alternate current direction, and wherein the plurality of differential transmission lines are arranged such that alternating current directions substantially eliminate cross-talk across the plurality of pairs of differential transmission lines.

[0005] In accordance with an embodiment, the plurality of pairs of differential transmission lines are substantially parallel to one another, and wherein pair of differential transmission lines is separated from each adjacent pair of differential transmission lines by a first distance, and wherein differential transmission lines in each pair of differential transmission lines are separated from one another by a second distance, and wherein the first distance is greater than the second distance.

[0006] In accordance with an embodiment, each pair of differential transmission lines includes a positive line and a negative line, and wherein the cross-coupling between i^{th} and j^{th} differential pair is a linear combination of cross-couplings of the positive and negative lines of each of the i^{th} and j^{th} differential pair with one another, wherein the cross-couplings of the positive and negative lines of each of the i^{th} and j^{th} differential pair with one another are each a function of a total distance between the i^{th} and j^{th} differential pair and currents traversing the i^{th} and j^{th} differential pair, and wherein the twists from the set of pairs of differential transmission lines substantially orthogonalize cross-couplings between each pair of differential transmission lines.

[0007] In accordance with an embodiment, the linear combination of cross-couplings of the positive and negative lines of each of the i^{th} and j^{th} differential pair with one another is:

$$\phi_{i,j} = \phi_{ia,ja} - \phi_{ia,jb} - \phi_{ib,ja} + \phi_{ib,jb};$$

where $\phi_{ia,ja}$ is the cross-coupling between the positive lines of the i^{th} and j^{th} differential pair, $\phi_{ia,jb}$ is the cross-coupling between the positive line of the i^{th} differential pair and the negative line of the j^{th} differential pair, $\phi_{ib,ja}$ is the cross-coupling between the negative line of the i^{th} differential pair and the positive line of the j^{th} differential pair, $\phi_{ib,jb}$ is the cross-coupling between the negative lines of the i^{th} and j^{th} differential pair, and wherein $\phi_{ia,ja}$, $\phi_{ia,jb}$, $\phi_{ib,ja}$, and $\phi_{ib,jb}$ are:

$$\phi_{i[n],j[m]} \propto \frac{1}{r_{eff}} = \frac{1}{l_{j[m]} l_{i[n]}} \int_{l_{j[m]}} \int_{l_{i[n]}} \frac{i_{i[n]}(l_{i[n]}) i_{j[m]}(l_{j[m]})}{r_{i[n],j[m]}} dl_{j[m]} dl_{i[n]};$$

where $n,m \in \{a,b\}$, $r_{i[n],j[m]}$ is the distance between i[n] and j[m], $l_{i[n]}$ is the length of transmission line i[n], $l_{j[m]}$ is the length of transmission line j[m], $i_{i[n]}(l_{i[n]})$ is the current through transmission line i[n] over length $l_{i[n]}$, and $i_{j[m]}(l_{j[m]})$ is the current through transmission line j[m] over length $l_{j[m]}$.

[0008] In accordance with an embodiment, the apparatus further comprises: a first pair of differential transmission lines from the plurality of pairs of differential transmission lines that does not include any twists and that has a first length; and a second pair of differential transmission lines from the set of pairs of differential transmission lines that has a second length and that is adjacent to the first pair of differential transmission lines, wherein the second length is approximately equal to the first length, and wherein the second pair of differential transmission lines includes a twist at a point about that is at about one-half of the second length.

[0009] In accordance with an embodiment, the apparatus further comprises an integrated circuit (IC) having: a first circuit formed on a substrate; a second circuit formed on the substrate;

and a communication channel formed on the substrate, wherein the communication channel includes the plurality of pairs of differential transmission lines that allow the first and second circuits to communicate with one another.

[0010] In accordance with an embodiment, the apparatus further comprises: a printed circuit board (PCB); a first IC that is secured to the PCB; a second IC that is secured to the PCB; and a communication channel formed on the PCB, wherein the communication channel includes the plurality of pairs of differential transmission lines that allow the first and second ICs to communicate with one another.

[0011] In accordance with an embodiment, an apparatus is provided. The apparatus comprises a first pair of differential transmission lines, wherein the differential transmission lines from the first pair are separated from one another by a first distance, and each differential transmission line from the first pair has a length; a second pair of differential transmission lines, wherein the differential transmission lines from the second pair are separated from one another by the first distance, and wherein each differential transmission line from the second pair has the length, and wherein the second pair is substantially parallel and adjacent to the first pair, and wherein the first pair is separated from the second pair by a second distance, and wherein the second distance is greater than the first distance; and a third pair of differential transmission lines, wherein the differential transmission lines from the third pair are separated from one another by the first distance, and wherein each differential transmission line from the third pair has the length, and wherein the third pair is substantially parallel and adjacent to the second pair, and wherein the third pair is separated from the second pair by the second distance, and wherein cross-coupling between the first, second, and third pairs is a function of currents traversing the first, second, and third pairs, and wherein the first, second, and third pairs of differential transmission lines are arranged such that the currents traversing the first, second, and third pairs of differential transmission lines substantially orthogonalize cross-couplings between each of the first, second, and third pairs.

[0012] In accordance with an embodiment, each of the second and third pairs include at least one twist to alternate current direction.

[0013] In accordance with an embodiment, each of the first, second, and third pairs includes a positive line and a negative line, and wherein the cross-coupling between i^{th} and j^{th} differential pair is a linear combination of cross-couplings of the positive and negative lines of each of the i^{th} and j^{th} differential pair with one another, wherein the cross-couplings of the positive and negative lines of each of the i^{th} and j^{th} differential pair with one another are each a function of a total distance between the i^{th} and j^{th} differential pair and currents traversing the i^{th} and j^{th} differential pair, and wherein the twists from the second and third pairs substantially orthogonalize cross-couplings between each pair of differential transmission lines.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Example embodiments are described with reference to accompanying drawings, wherein:

[0015] FIGS. 1A through 4B depict examples of communication channels using a coupling orthogonalization approach;

[0016] FIG. 5 is an example of an integrated circuit (IC) that uses the type of communication depicted in FIGS. 1A to 4B;

[0017] FIG. 6A is an area of the communication for FIG. 5 depicting a twist in pair 104;

[0018] FIG. 6B is a cross-sectional view of the pair 104 along section line 1-1 of FIG. 6A;

[0019] FIG. 6C is a cross-sectional view of the pair 104 along section line 2-2 of FIG. 6A;

[0020] FIG. 7 is an example of a printed circuit board (PCB) that uses the type of communication channel depicted in FIGS. 1A to 4B; and

[0021] FIG. 8 is an example of system that uses the type of communication channel depicted in FIGS. 1A to 4B.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0022] Differential signaling generally employs pairs of conductors that each carry a portion of a differential signal (i.e., positive and negative portions), and, as is well-know, electromagnetic fields are generate in the volume surrounding conductors when a signal is traversing the conductor. When signals traverse differential pairs, though, there generally is no intra-pair coupling or cross-talk because the currents in the pair of conductors have the same magnitude, but different directions. This means that the electromagnetic fields cancel each other and that conductor pairs can be closely spaced (i.e., very near to one another or have a narrow pitch). There can, however, be intra-pair coupling between adjacent or near-by pairs of conductors. Typically, the coupling or cross-talk between these adjacent or near-by pairs of conductors is a function of the distance and the currents traversing the conductors.

[0023] In FIG. 1A, pairs 102 and 104 can be seen. Each of these pair 102 and 104 includes conductors that carry a positive portion of a differential signal (i.e., 1a and 2a, respectively) and a conductor that carries a negative portion of a differential signal (i.e., 1b and 2b, respectively). In this example, the pitch or distance between the intra-pair conductors or transmission lines (i.e., between 1a and 1b) is less than the pitch or distance between pairs 102 and 104. The coupling or cross-talk for this communication channel 100-1 would also be a linear combination of the couplings between each of the conductors, which is as follows:

(1)
$$\begin{aligned}\phi_{1,2} &= \phi_{1a,1b} + \phi_{2a,2b} + \phi_{1a,2a} - \phi_{1a,2b} - \phi_{1b,2a} + \phi_{1b,2b} \\ &= +\phi_{1a,2a} - \phi_{1a,2b} - \phi_{1b,2a} + \phi_{1b,2b}\end{aligned}$$

The coupling (Φ) is a function of the total distance between the conductors and currents traversing the conductors, substantially having the following form:

(2)
$$\phi_{i[n],j[m]} \propto \frac{1}{r_{eff}} = \frac{1}{l_{j[m]}l_{i[n]}} \int_{l_{j[m]}} \int_{l_{i[n]}} \frac{i_{i[n]}(l_{i[n]})\, i_{j[m]}(l_{j[m]})}{r_{i[n],j[m]}} \, dl_{j[m]} dl_{i[n]}$$

where $n,m \in \{a,b\}$, $r_{i[n],j[m]}$ is the distance between conductors or transmission lines i[n] and j[m], $l_{i[n]}$ is the length of transmission line i[n], $l_{j[m]}$ is the length of transmission line j[m], $i_{i[n]}(l_{i[n]})$ is the current through transmission line i[n] over length $l_{i[n]}$, and $i_{j[m]}(l_{j[m]})$ is the current through transmission line j[m] over length $l_{j[m]}$. For the communication channel 100-1, the couplings or cross-talk would be:

(3)
$$\phi_{1a,2a} \propto \frac{1}{l_{1a}l_{2a}} \int_{l_{1a}} \int_{l_{2a}} \frac{i_{1a}(l_{1a})\, i_{2a}(l_{2a})}{r_{1a,2a}} \, dl_{1a} dl_{2a} \,;$$

(4)
$$\phi_{1a,2b} \propto \frac{1}{l_{1a}l_{2b}} \int_{l_{1a}} \int_{l_{2b}} \frac{i_{1a}(l_{1a})\, i_{2b}(l_{2ba})}{r_{1a,2b}} \, dl_{1a} dl_{2b} \,;$$

(5)
$$\phi_{1b,2a} \propto \frac{1}{l_{1b}l_{2a}} \int_{l_{1b}} \int_{l_{2a}} \frac{i_{1b}(l_{1b})\, i_{2a}(l_{2a})}{r_{1b,2a}} \, dl_{1b} dl_{2a} \,;$$

(6) $$\phi_{1b,2b} \propto \frac{1}{l_{1b}l_{2b}} \int_{l_{1b}} \int_{l_{2b}} \frac{i_{1a}(l_{1a}) i_{2b}(l_{2b})}{r_{1b,2b}} dl_{1b} dl_{2b};$$

[0024] Understanding that the field for intra-pair conductors (i.e., 1a and 1b) is cancelled because the current directions are opposite one another, this condition can be thought of as orthogonality. This “orthogonality” can be extended to inter-pair fields by introducing twists (i.e., 118-1) to swap the current direction. These twists within the differential pairs (i.e., 102 and 104) can be spaced along the differential pairs (i.e., 104) in patterns such that the coupling between each pair is substantially zero.

[0025] Looking first to FIGS. 1A and 1B, orthogonality between pairs 102 and 104 can be seen. For pair 102, there are no twists, and, as shown, the collective current for pair 102 can be expressed as “+1.” If a twist 118-1 is introduced to pair 104 at point halfway along the length of pair 102 (which has a length that is approximately the same as pair 102 and where distance D1 is approximately equal to distance D2), the current for pair 104 can be expressed as “+1” along distance D1 and “-1” along distance D2. This would mean that equations (2) to (5) above would become:

(7) $$\phi_{1a,2a} \propto \frac{1}{l_{1a}l_{2a}} \left[\begin{array}{l} \int_0^{\frac{l_{2a}}{2}} \int_{l_{1a}} \frac{i_{1a}(l_{1a}) i_{2a}(l_{2a})}{r_{1a,2a}} dl_{1a} dl_{2a} - \\ \int_{\frac{l_{2a}}{2}}^{l_{2a}} \int_{l_{1a}} \frac{i_{1a}(l_{1a}) i_{2a}(l_{2a})}{r_{1a,2a}} dl_{1a} dl_{2a} \end{array} \right]$$

(8) $$\phi_{1a,2b} \propto \frac{1}{l_{1a}l_{2b}} \left[\begin{array}{l} \int_0^{\frac{l_{2b}}{2}} \int_{l_{1a}} \frac{i_{1a}(l_{1a}) i_{2b}(l_{2b})}{r_{1a,2b}} dl_{1a} dl_{2b} - \\ \int_{\frac{l_{2b}}{2}}^{l_{2b}} \int_{l_{1a}} \frac{i_{1a}(l_{1a}) i_{2b}(l_{2b})}{r_{1a,2b}} dl_{1a} dl_{2b} \end{array} \right]$$

(9) $$\phi_{1b,2a} \propto \frac{1}{l_{1b}l_{2a}} \left[\begin{array}{l} \int_0^{\frac{l_{2a}}{2}} \int_{l_{1b}} \frac{i_{1b}(l_{1b}) i_{2a}(l_{2a})}{r_{1b,2a}} dl_{1b} dl_{2a} - \\ \int_{\frac{l_{2a}}{2}}^{l_{2a}} \int_{l_{1b}} \frac{i_{1b}(l_{1b}) i_{2a}(l_{2a})}{r_{1b,2a}} dl_{1b} dl_{2a} \end{array} \right]$$

$$\phi_{1b,2b} \propto \frac{1}{l_{1b}l_{2b}}\left[\begin{array}{l}\int_0^{\frac{l_{2b}}{2}}\int_{l_{1b}}\frac{i_{1b}(l_{1b})i_{2b}(l_{2b})}{r_{1b,2b}}dl_{1b}dl_{2b} - \\ \int_{\frac{l_{2b}}{2}}^{l_{2b}}\int_{l_{1b}}\frac{i_{1b}(l_{1b})i_{2b}(l_{2b})}{r_{1b,2b}}dl_{1b}dl_{2b}\end{array}\right] \tag{10}$$

Substituting equations (7) through (10) into equation (1), the coupling between pairs 102 and 104 would be:

$$\begin{aligned}
\phi_{1,2} &= +\phi_{1a,2a} - \phi_{1a,2b} - \phi_{1b,2a} + \phi_{1b,2b} \\
&= \frac{1}{l_{1a}l_{2a}}\int_0^{\frac{l_{2a}}{2}}\int_{l_{1a}}\frac{i_{1a}(l_{1a})i_{2a}(l_{2a})}{r_{1a,2a}}dl_{1a}dl_{2a} - \\
&\frac{1}{l_{1a}l_{2a}}\int_{\frac{l_{2a}}{2}}^{l_{2a}}\int_{l_{1a}}\frac{i_{1a}(l_{1a})i_{2a}(l_{2a})}{r_{1a,2a}}dl_{1a}dl_{2a} - \\
&\frac{1}{l_{1a}l_{2b}}\int_0^{\frac{l_{2b}}{2}}\int_{l_{1a}}\frac{i_{1a}(l_{1a})i_{2b}(l_{2b})}{r_{1a,2b}}dl_{1a}dl_{2b} + \\
&\frac{1}{l_{1a}l_{2b}}\int_{\frac{l_{2b}}{2}}^{l_{2b}}\int_{l_{1a}}\frac{i_{1a}(l_{1a})i_{2b}(l_{2b})}{r_{1a,2b}}dl_{1a}dl_{2b} - \\
&\frac{1}{l_{1b}l_{2a}}\int_0^{\frac{l_{2a}}{2}}\int_{l_{1b}}\frac{i_{1b}(l_{1b})i_{2a}(l_{2a})}{r_{1b,2a}}dl_{1b}dl_{2a} + \\
&\frac{1}{l_{1b}l_{2a}}\int_{\frac{l_{2a}}{2}}^{l_{2a}}\int_{l_{1b}}\frac{i_{1b}(l_{1b})i_{2a}(l_{2a})}{r_{1b,2a}}dl_{1b}dl_{2a} + \\
&\frac{1}{l_{1b}l_{2b}}\int_0^{\frac{l_{2b}}{2}}\int_{l_{1b}}\frac{i_{1b}(l_{1b})i_{2b}(l_{2b})}{r_{1b,2b}}dl_{1b}dl_{2b} - \\
&\frac{1}{l_{1b}l_{2b}}\int_{\frac{l_{2b}}{2}}^{l_{2b}}\int_{l_{1b}}\frac{i_{1b}(l_{1b})i_{2b}(l_{2b})}{r_{1b,2b}}dl_{1b}dl_{2b}
\end{aligned} \tag{11}$$

For reasonably short lines (i.e., less than 1/10 of a wavelength), twist 118-1 (positioned halfway along the length of pair 104) will result in the coupling between pairs 102 and 104 (i.e., equation 11) to be zero.

[0026] Orthogonality between three pairs 102, 104, and 106 in communication channel 100-2 can be seen in FIGS. 2A and 2B. In this example, pair 106 includes twists 118-2 and 118-3 so that the current for pair 106 can be represents as "+1" along distance D3, "-1" along distance D4, and "+1" along distance D5. As shown, these current directions (representations) are a function of distance along the length of the pairs (i.e., 102 and 104), which has the effect of creating a binary looking current distribution versus distance. Thus, by adjusting distances D1 through D5, orthogonality between pairs 102, 104, and 106, meaning that the inter-pair couplings between the pairs 102, 104, and 106 are approximately zero.

[0027] FIGS. 3A to 4B show examples of communication channels 100-3 and 100-4 (which have 4 and 8 pairs, respectively). Similar to communication channels 100-1 and 100-2, pairs 108, 110, 112, 114, and 116 have twists spaced along distances D6 through D37. These distances, too, can be adjusted to achieve inter-pair couplings between the pairs 108, 110, 112, 114, and 116 are approximately zero, which demonstrates that this orthogonalization scheme can be extended to any number of pairs of differential lines.

[0028] FIG. 5 illustrates an integrated circuit (IC) 500 that employs a communication channel like 100-1 to 100-4 (referred to hereinafter as 100). For this IC 500, there are (for example) two circuits 502 and 504, which are formed on substrate 506, with the communication channel 100 formed therebetween. The communication channel 100 can include any number of pairs of differential lines or conductors, but for the sake of simplicity two are shown (102 and 104).

[0029] Looking to area 506, pairs 102 and 104 are shown in greater detail in FIG. 6A through 6C. Specifically, twist 118-1 be seen. Typically, each of the conductors (i.e., 1a) is formed of a conductive strip of metal (which is a portion of a metallization layer). Here, the conductors 2a and 2b are formed by metallization layer 606 (which can, for example, be aluminum or copper), being portions 606-1 and 606-2, which is formed over layer 604 (which may comprise several layers). For the twist 118-1, vias (i.e., 608), which may be formed of tungsten, couple metallization layer 606 to metallization layer 610 (which may also be formed of copper or aluminum). To support and isolate metallization layer 610 and via 608, dielectric material (i.e., silicon dioxide) can use used in one or more layers.

[0030] FIGS. 7 and 8 illustrate other uses for the communication channel 100. For example, in FIG. 7, communication channel 100 can be used for communication between ICs 704 and 706 (or between pins of one of the ICs 704 or 706) on a printed circuit board (PCB) 702. Alternatively, communication channel 100 (in the example of FIG. 8) can be used to communicate between devices 802 and 804.

[0031] Those skilled in the art to which the invention relates will appreciate that modifications may be made to the described embodiments, and also that many other embodiments are possible, without departing from the scope of the claimed invention.

CLAIMS

What is claimed is:

1. An apparatus comprising a plurality of pairs of differential transmission lines, wherein the plurality of pairs of differential transmission lines includes a set of pairs of differential transmission lines with each pair of differential transmission lines from the set of pairs of differential transmission lines including at least one twist to alternate current direction, and wherein the lines of the plurality of differential transmission lines are arranged such that alternating current directions substantially eliminate cross-talk across the plurality of pairs of differential transmission lines.

2. The apparatus of Claim 1, wherein the plurality of pairs of differential transmission lines are substantially parallel to one another, and wherein pair of differential transmission lines is separated from each adjacent pair of differential transmission lines by a first distance, and wherein differential transmission lines in each pair of differential transmission lines are separated from one another by a second distance, and wherein the first distance is greater than the second distance.

3. The apparatus of Claim 2, wherein each pair of differential transmission lines includes a positive line and a negative line, and wherein the cross-coupling between i^{th} and j^{th} differential pair is a linear combination of cross-couplings of the positive and negative lines of each of the i^{th} and j^{th} differential pair with one another, wherein the cross-couplings of the positive and negative lines of each of the i^{th} and j^{th} differential pair with one another are each a function of a total distance between the i^{th} and j^{th} differential pair and currents traversing the i^{th} and j^{th} differential pair, and wherein the twists from the set of pairs of differential transmission lines substantially orthogonalize cross-couplings between each pair of differential transmission lines.

[0032] 4. The apparatus of Claim 3, wherein the linear combination of cross-couplings of the positive and negative lines of each of the i^{th} and j^{th} differential pair with one another is:

$$\phi_{i,j} = \phi_{ia,ja} - \phi_{ia,jb} - \phi_{ib,ja} + \phi_{ib,jb};$$

where $\phi_{ia,ja}$ is the cross-coupling between the positive lines of the i[th] and j[th] differential pair, $\phi_{ia,jb}$ is the cross-coupling between the positive line of the i[th] differential pair and the negative line of the j[th] differential pair, $\phi_{ib,ja}$ is the cross-coupling between the negative line of the i[th] differential pair and the positive line of the j[th] differential pair, $\phi_{ib,jb}$ is the cross-coupling between the negative lines of the i[th] and j[th] differential pair, and wherein $\phi_{ia,ja}$, $\phi_{ia,jb}$, $\phi_{ib,ja}$, and $\phi_{ib,jb}$ are:

$$\phi_{i[n],j[m]} \propto \frac{1}{r_{eff}} = \frac{1}{l_{j[m]} l_{i[n]}} \int_{l_{j[m]}} \int_{l_{i[n]}} \frac{i_{i[n]}(l_{i[n]}) i_{j[m]}(l_{j[m]})}{r_{i[n],j[m]}} dl_{j[m]} dl_{i[n]} \; ;$$

where $n,m \in \{a,b\}$, $r_{i[n],j[m]}$ is the distance between i[n] and j[m], $l_{i[n]}$ is the length of transmission line i[n], $l_{j[m]}$ is the length of transmission line j[m], $i_{i[n]}(l_{i[n]})$ is the current through transmission line i[n] over length $l_{i[n]}$, and $i_{j[m]}(l_{j[m]})$ is the current through transmission line j[m] over length $l_{j[m]}$.

5. The apparatus of Claim 4, wherein the apparatus further comprises:

a first pair of differential transmission lines from the plurality of pairs of differential transmission lines that does not include any twists and that has a first length; and

a second pair of differential transmission lines from the set of pairs of differential transmission lines that has a second length and that is adjacent to the first pair of differential transmission lines, wherein the second length is approximately equal to the first length, and wherein the second pair of differential transmission lines includes a twist at a point about that is at about one-half of the second length.

6. The apparatus of Claim 4, wherein the apparatus further comprises an integrated circuit (IC) having:

a first circuit formed on a substrate;

a second circuit formed on the substrate; and

a communication channel formed on the substrate, wherein the communication channel includes the plurality of pairs of differential transmission lines that allow the first and second circuits to communicate with one another.

7. The apparatus of Claim 4, wherein the apparatus further comprises:

a printed circuit board (PCB);

a first IC that is secured to the PCB;

a second IC that is secured to the PCB; and

a communication channel formed on the PCB, wherein the communication channel includes the plurality of pairs of differential transmission lines that allow the first and second ICs to communicate with one another.

8. An apparatus comprising:

a first pair of differential transmission lines, wherein the differential transmission lines from the first pair are separated from one another by a first distance, and each differential transmission line from the first pair has a length;

a second pair of differential transmission lines, wherein the differential transmission lines from the second pair are separated from one another by the first distance, and wherein each differential transmission line from the second pair has the length, and wherein the second pair is substantially parallel and adjacent to the first pair, and wherein the first pair is separated from the second pair by a second distance, and wherein the second distance is greater than the first distance; and

a third pair of differential transmission lines, wherein the differential transmission lines from the third pair are separated from one another by the first distance, and wherein each differential transmission line from the third pair has the length, and wherein the third pair is substantially parallel and adjacent to the second pair, and wherein the third pair is separated from the second pair by the second distance, and wherein cross-coupling between the first, second, and third pairs is a function of currents traversing the first, second, and third pairs, and wherein the first, second, and third pairs of differential transmission lines are arranged such that the currents traversing the first, second, and third pairs of differential transmission lines substantially orthogonalize cross-couplings between each of the first, second, and third pairs.

9. The apparatus of Claim 8, wherein each of the second and third pairs include at least one twist to alternate current direction.

10. The apparatus of Claim 9, wherein each of the first, second, and third pairs includes a positive line and a negative line, and wherein the cross-coupling between ith and jth differential pair is a linear combination of cross-couplings of the positive and negative lines of each of the ith and jth differential pair with one another, wherein the cross-couplings of the positive and negative lines of each of the ith and jth differential pair with one another are each a function of a total distance between the ith and jth differential pair and currents traversing the ith and jth differential pair, and wherein the twists from the second and third pairs substantially orthogonalize cross-couplings between each pair of differential transmission lines.

11. The apparatus of Claim 10, wherein the linear combination of cross-couplings of the positive and negative lines of each of the ith and jth differential pair with one another is:

$$\phi_{i,j} = \phi_{ia,ja} - \phi_{ia,jb} - \phi_{ib,ja} + \phi_{ib,jb};$$

where $\phi_{ia,ja}$ is the cross-coupling between the positive lines of the ith and jth differential pair, $\phi_{ia,jb}$ is the cross-coupling between the positive line of the ith differential pair and the negative line of the jth differential pair, $\phi_{ib,ja}$ is the cross-coupling between the negative line of the ith differential pair and the positive line of the jth differential pair, $\phi_{ib,jb}$ is the cross-coupling between the negative lines of the ith and jth differential pair, and wherein $\phi_{ia,ja}$, $\phi_{ia,jb}$, $\phi_{ib,ja}$, and $\phi_{ib,jb}$ are:

$$\phi_{i[n],j[m]} \propto \frac{1}{r_{eff}} = \frac{1}{l_{j[m]} l_{i[n]}} \int_{l_{j[m]}} \int_{l_{i[n]}} \frac{i_{i[n]}(l_{i[n]}) i_{j[m]}(l_{j[m]})}{r_{i[n],j[m]}} dl_{j[m]} dl_{i[n]};$$

where $n,m \in \{a,b\}$, $r_{i[n],j[m]}$ is the distance between i[n] and j[m], $l_{i[n]}$ is the length of transmission line i[n], $l_{j[m]}$ is the length of transmission line j[m], $i_{i[n]}(l_{i[n]})$ is the current through transmission line i[n] over length $l_{i[n]}$, and $i_{j[m]}(l_{j[m]})$ is the current through transmission line j[m] over length $l_{j[m]}$.

12. The apparatus of Claim 11, wherein the second pair includes a twist at a point about that is at about one-half of the second length.

13. The apparatus of Claim 11, wherein the apparatus further comprises an IC having:

a first circuit formed on a substrate;

a second circuit formed on the substrate; and

a communication channel formed on the substrate, wherein the communication channel includes the plurality of pairs of differential transmission lines that allow the first and second circuits to communicate with one another.

14. The apparatus of claim 13, wherein the apparatus further comprises:

a PCB;

a first IC that is secured to the PCB;

a second IC that is secured to the PCB; and

a communication channel formed on the PCB, wherein the communication channel includes the plurality of pairs of differential transmission lines that allow the first and second ICs to communicate with one another.

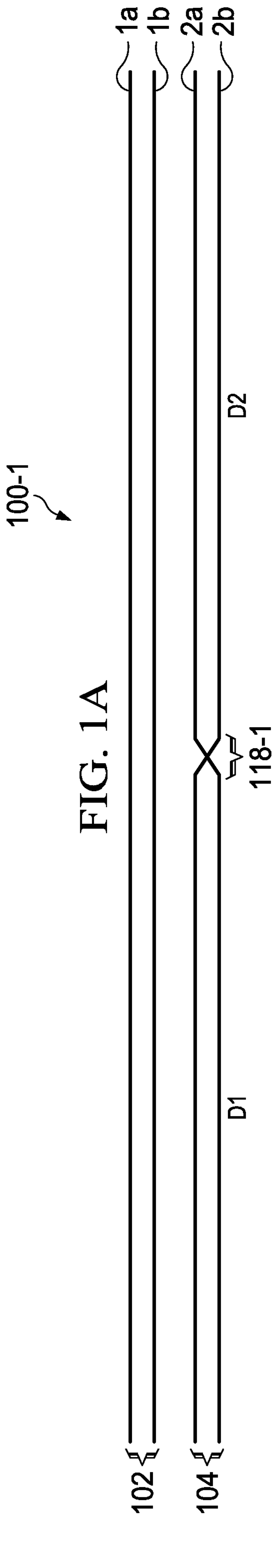

100-1
1a
1b
2a
2b
D1
D2
118-1
102
104

FIG. 1A

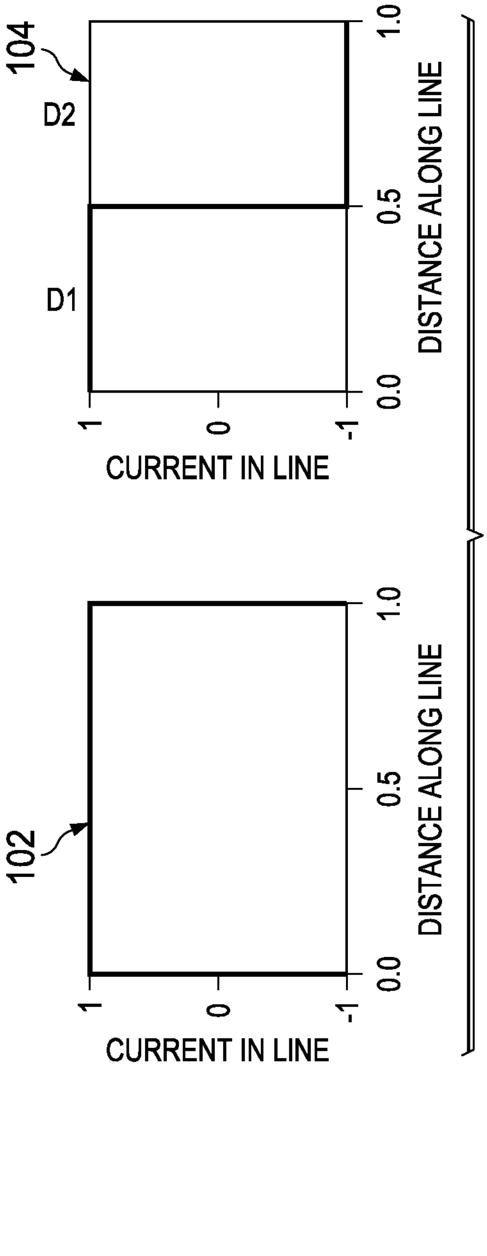

102
CURRENT IN LINE
DISTANCE ALONG LINE
1
0
-1
0.0
0.5
1.0
104
D1
D2
CURRENT IN LINE
DISTANCE ALONG LINE
1
0
-1
0.0
0.5
1.0

FIG. 1B

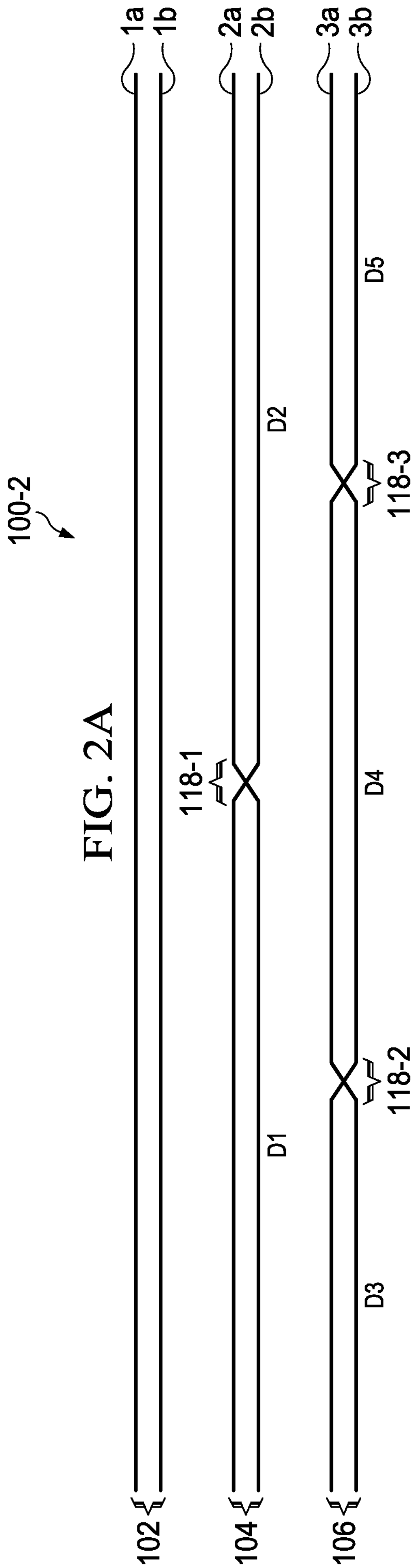

100-2
1a
1b
2a
2b
3a
3b
102
104
106
118-1
118-2
118-3
D1
D2
D3
D4
D5

FIG. 2A

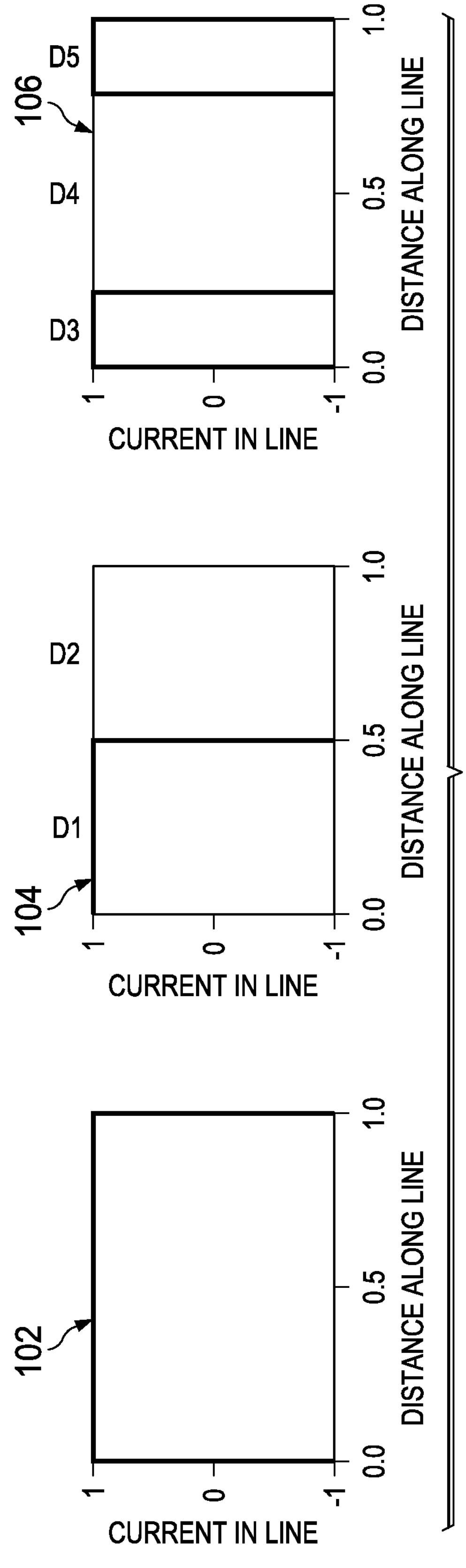

102
104
106
D1
D2
D3
D4
D5
CURRENT IN LINE
DISTANCE ALONG LINE
1
0
-1
0.0
0.5
1.0

FIG. 2B

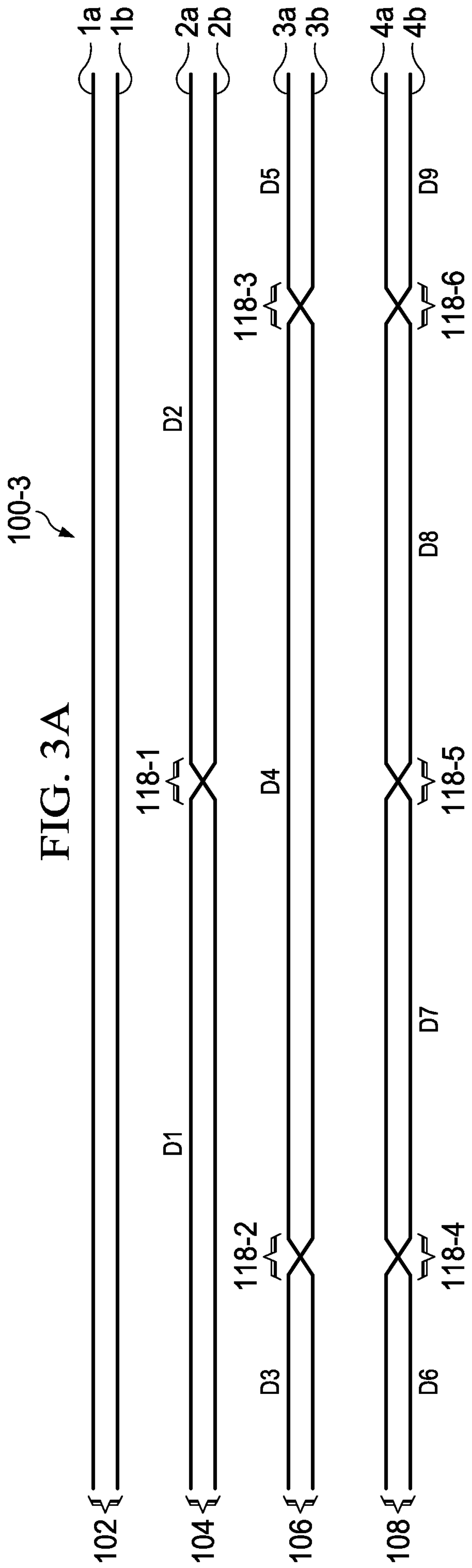

100-3
1a
1b
2a
2b
3a
3b
4a
4b
102
104
106
108
D1
D2
D3
D4
D5
D6
D7
D8
D9
118-1
118-2
118-3
118-4
118-5
118-6

FIG. 3A

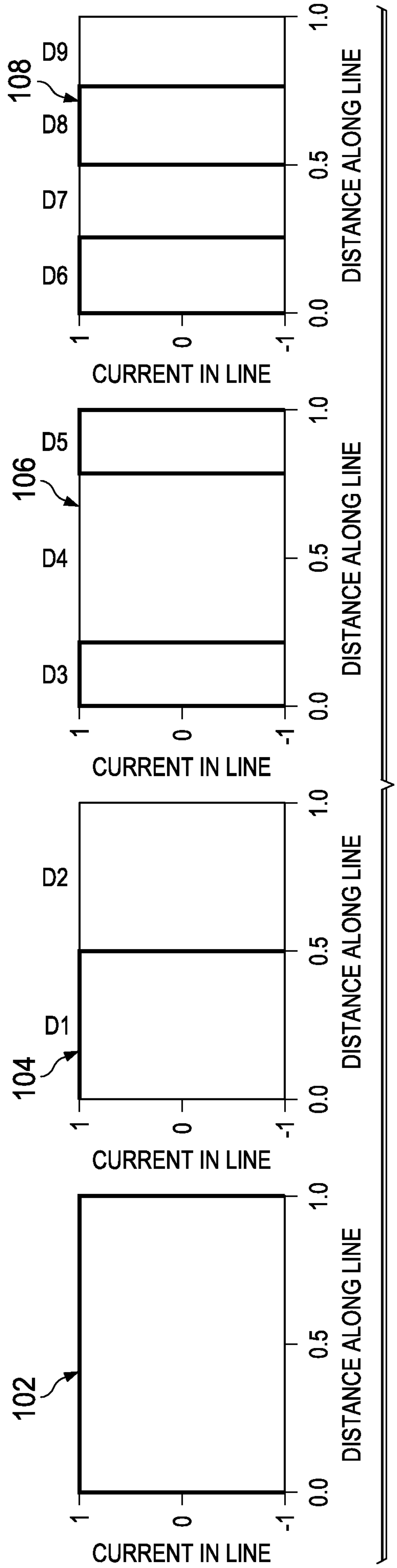

102
104
106
108
D1
D2
D3
D4
D5
D6
D7
D8
D9
CURRENT IN LINE
DISTANCE ALONG LINE
1
0
-1
0.0
0.5
1.0

FIG. 3B

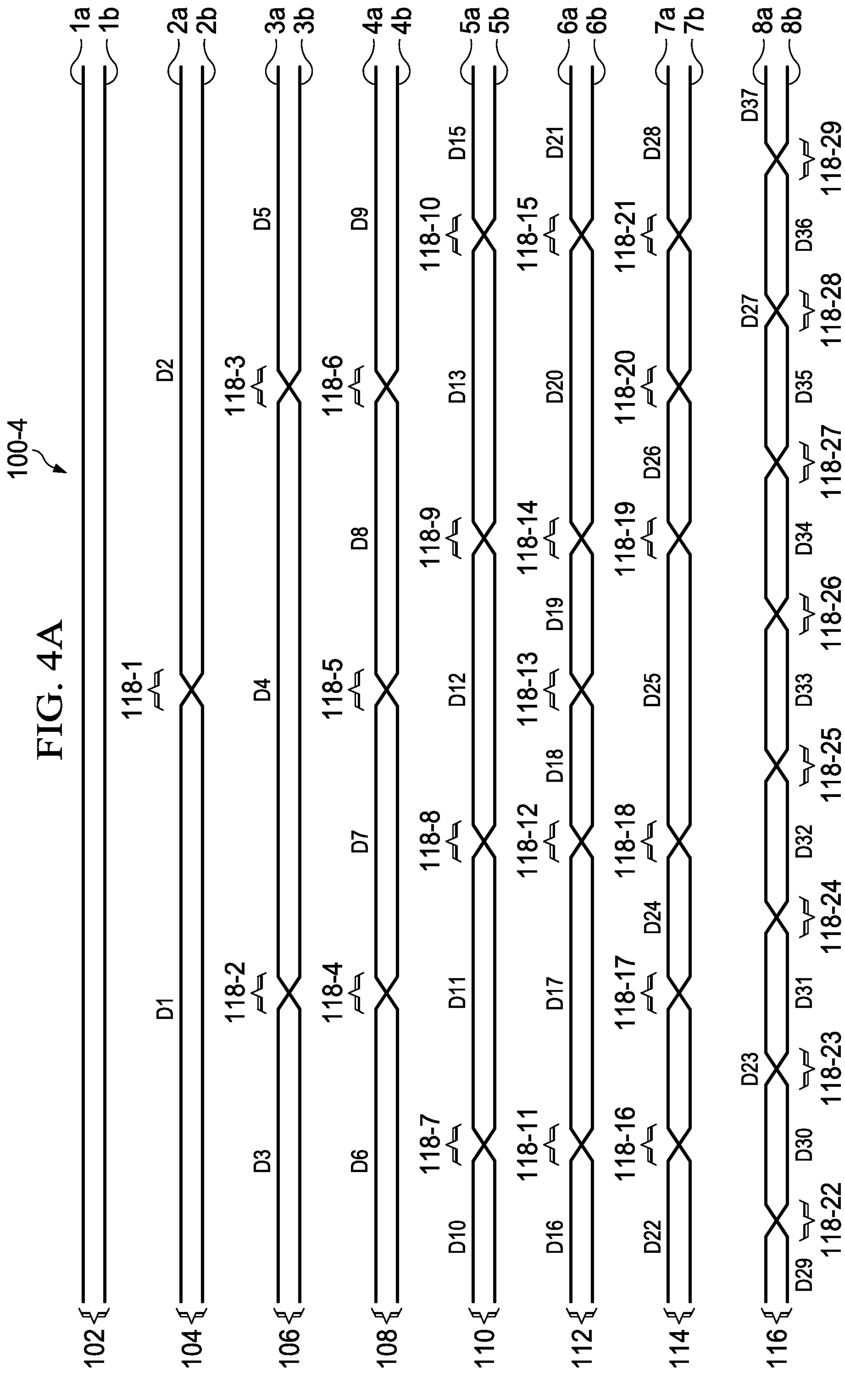

100-4
1a
1b
2a
2b
3a
3b
4a
4b
5a
5b
6a
6b
7a
7b
8a
8b
102
104
106
108
110
112
114
116
D1
D2
D3
D4
D5
D6
D7
D8
D9
D10
D11
D12
D13
D15
D16
D17
D18
D19
D20
D21
D22
D23
D24
D25
D26
D27
D28
D29
D30
D31
D32
D33
D34
D35
D36
D37
118-1
118-2
118-3
118-4
118-5
118-6
118-7
118-8
118-9
118-10
118-11
118-12
118-13
118-14
118-15
118-16
118-17
118-18
118-19
118-20
118-21
118-22
118-23
118-24
118-25
118-26
118-27
118-28
118-29

FIG. 4A

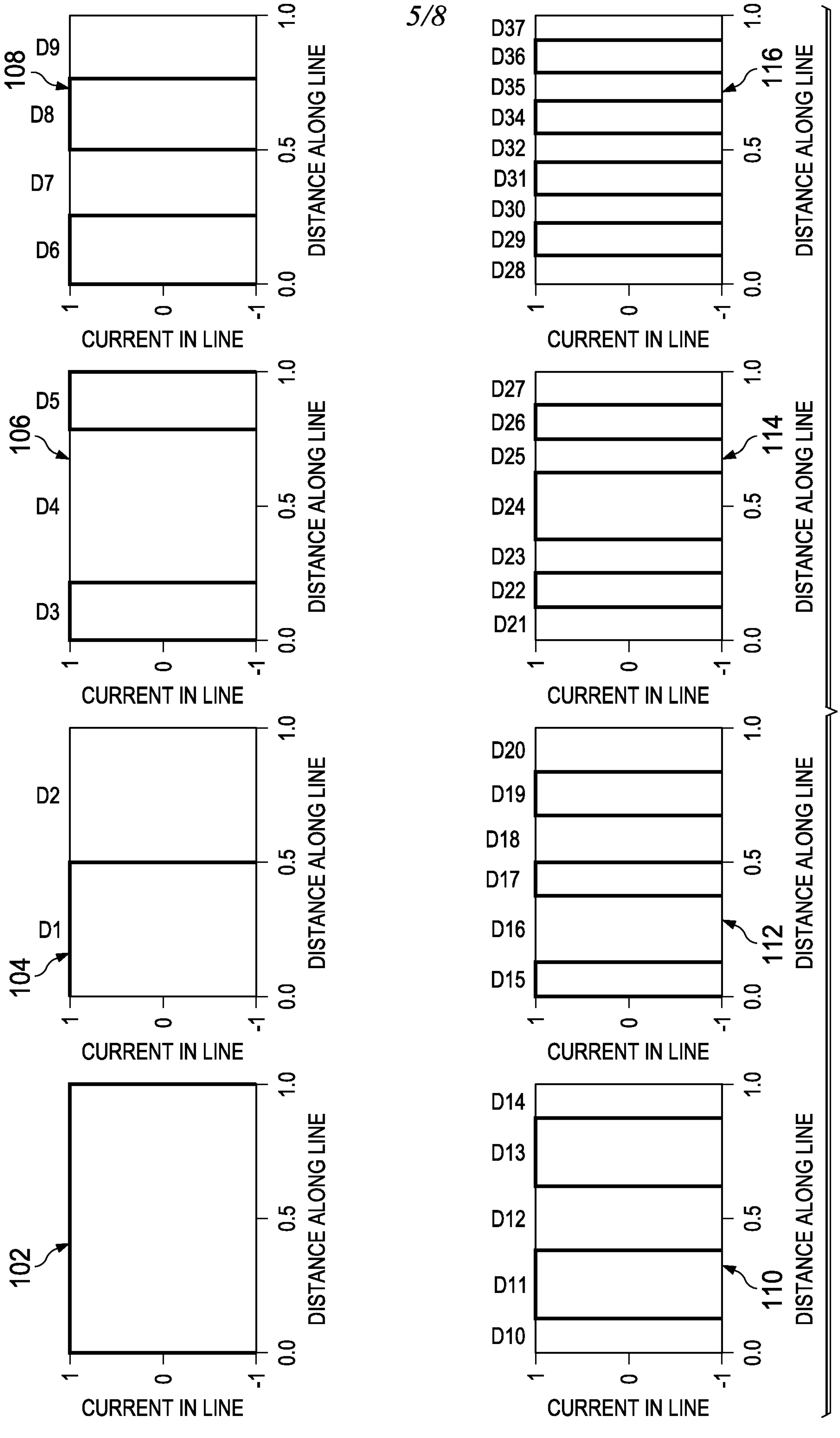

CURRENT IN LINE
DISTANCE ALONG LINE
1
0
-1
0.0
0.5
1.0
102
104
106
108
110
112
114
116
D1
D2
D3
D4
D5
D6
D7
D8
D9
D10
D11
D12
D13
D14
D15
D16
D17
D18
D19
D20
D21
D22
D23
D24
D25
D26
D27
D28
D29
D30
D31
D32
D34
D35
D36
D37

FIG. 4B

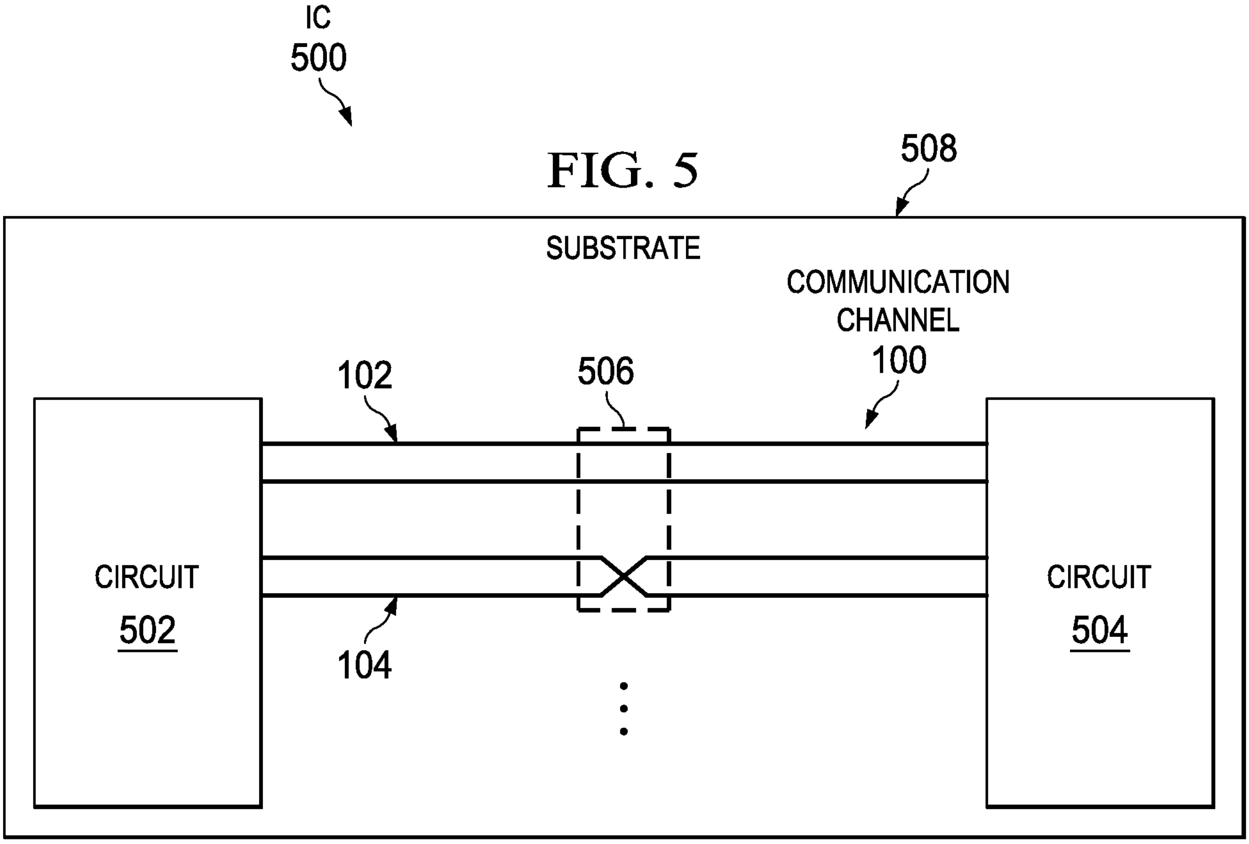
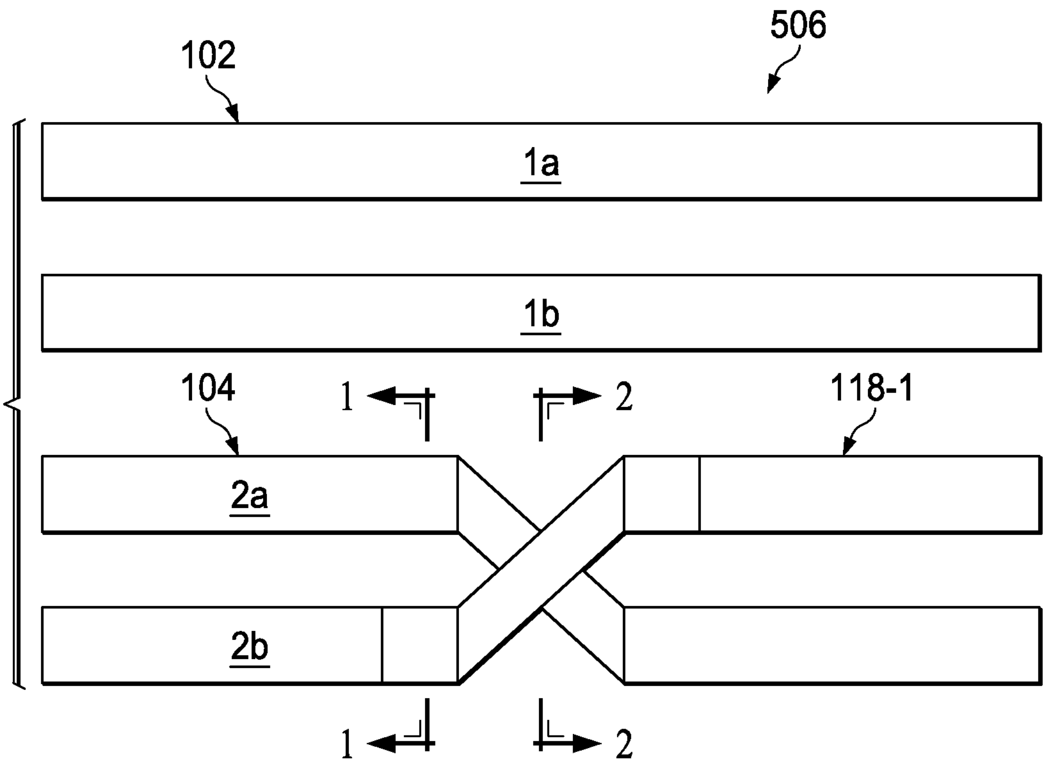
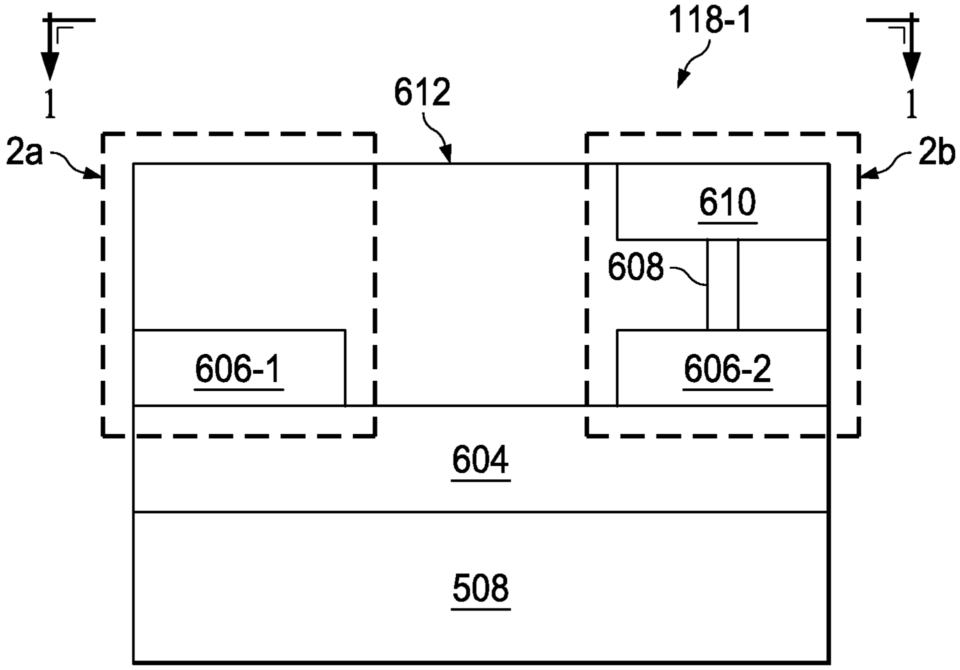

IC
500
508
SUBSTRATE
COMMUNICATION
CHANNEL
100
102
506
CIRCUIT
502
104
CIRCUIT
504

FIG. 5

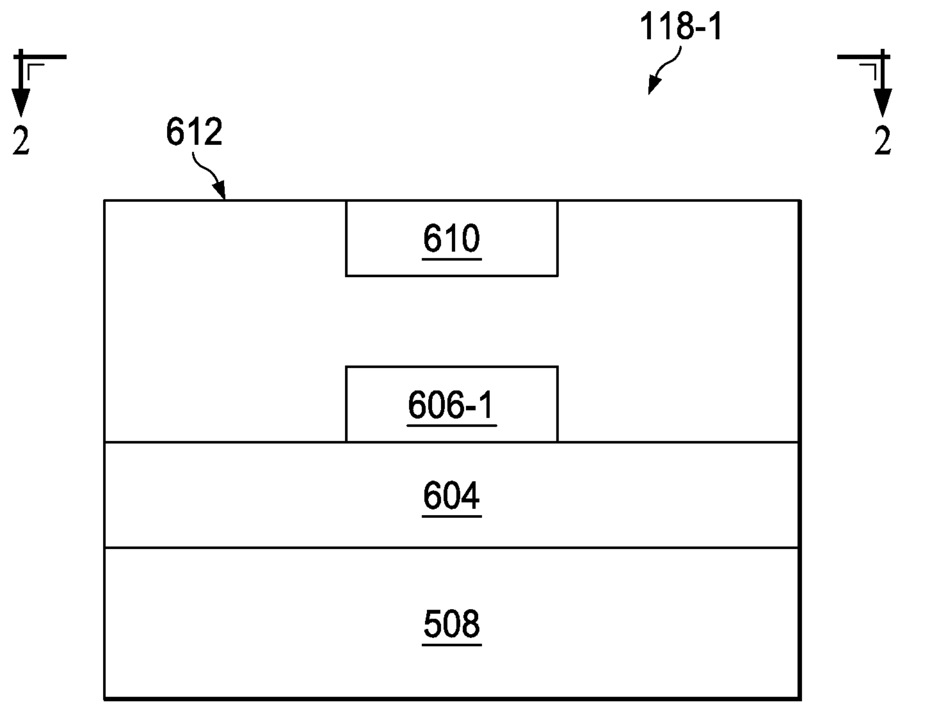
FIG. 6A


506
102
1a
1b
104
118-1
1
2
2a
2b
1
2



118-1
1
1
612
2a
2b
610
608
606-1
606-2
604
508

FIG. 6B



118-1
2
2
612
610
606-1
604
508

FIG. 6C

FIG. 7

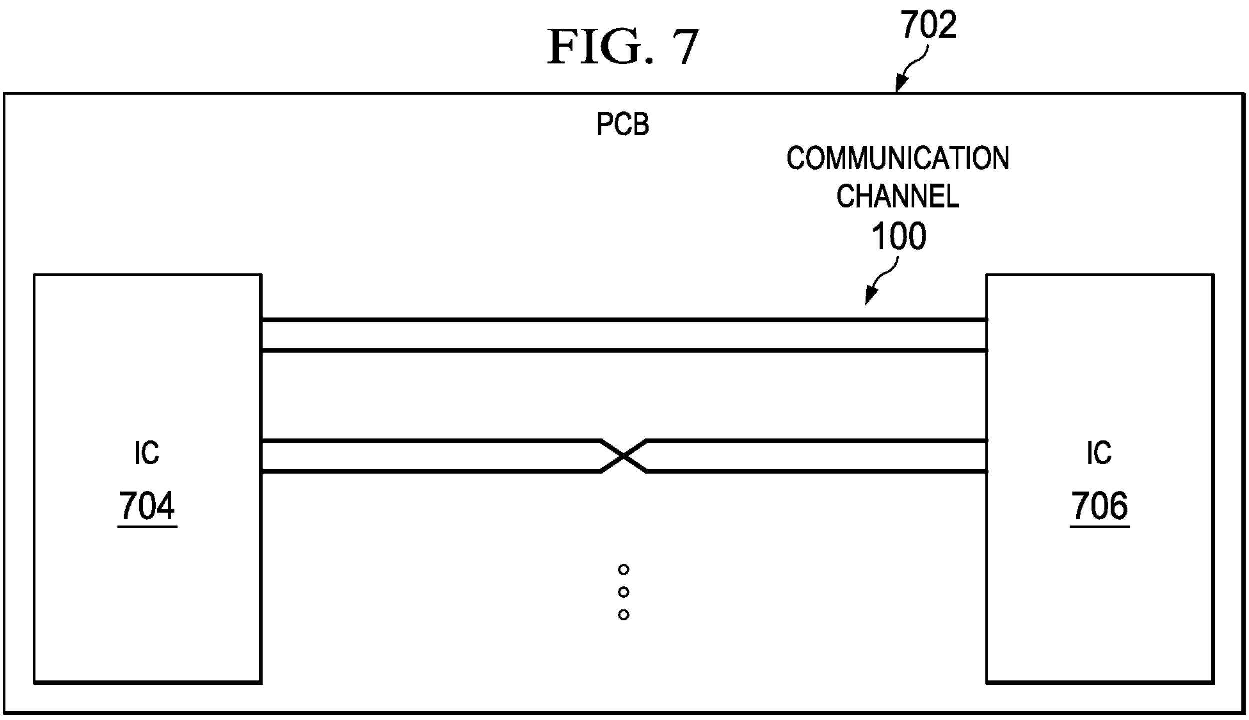
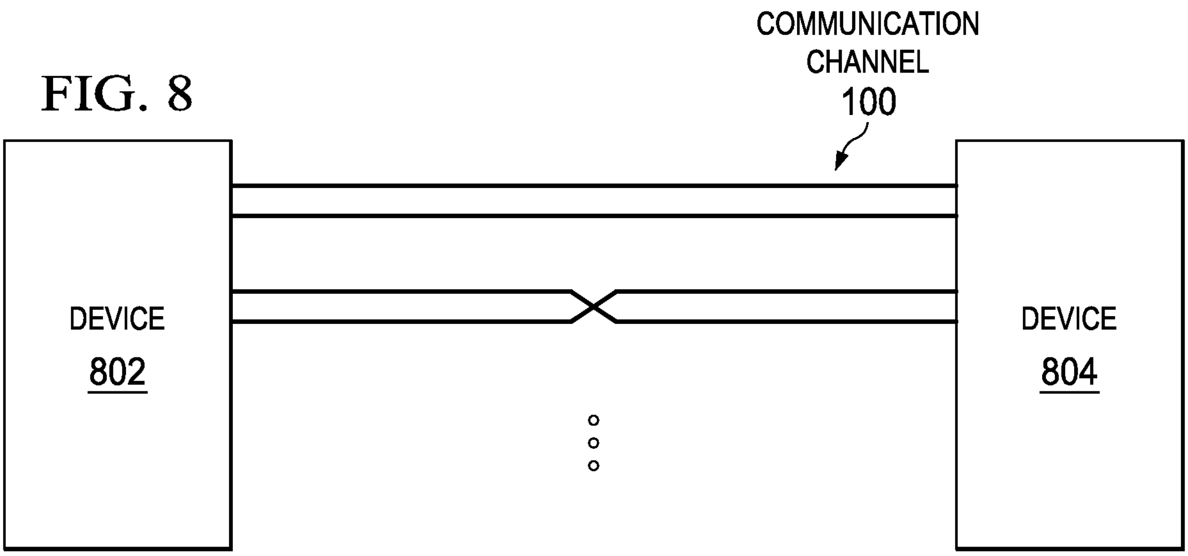

702
PCB
COMMUNICATION CHANNEL 100
IC
704
IC
706

FIG. 8


COMMUNICATION CHANNEL 100
DEVICE
802
DEVICE
804