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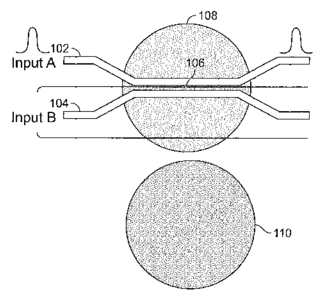

FIG. 1

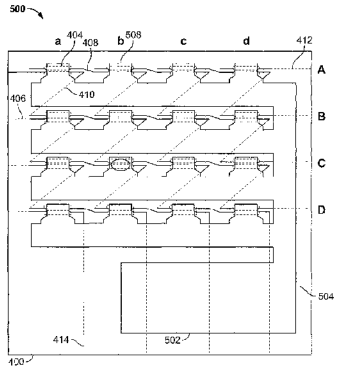

FIG. 6

(57) **Abstract:** An optical switch network includes an array of electro-wetting on dielectric (EWOD)-actuated optical switches associated with one or more input and output waveguides. The optical switches, which are formed by waveguide couplers, are arranged in rows and columns and are interconnected via interconnecting waveguides. A microchannel network distributes droplets of electro-wetting liquid to the optical switches and has a first microchannel disposed along a first row or column of optical switches for distributing droplets of electro-wetting liquid to the optical switches of the first row or column and a second microchannel disposed proximate the second row or column of optical switches for distributing droplets of electro-wetting liquid to the optical switches of the second row or column. In some embodiments, no more than one droplet of electro-wetting liquid is moveable along the first microchannel to address the optical switches in the first row or column.

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ELECTRO-WETTING ON DIELECTRIC-BASED INTEGRATED OPTICAL SWITCH NETWORK WITH HIGH PERFORMANCE AND COMPACT CONFIGURATION

Cross-Reference to Related Application

This application claims the benefit of U.S. Patent Application Serial No. 62/331,777, filed on May 4, 2016, the disclosure of which is incorporated herein by reference in its entirety.

Field of the Invention

This invention is related to optical fiber data communication systems and to optical switch systems used in such systems for controlling and managing optical signals.

Background of the Invention

Optical fiber networks are becoming prevalent in part because service providers want to deliver high bandwidth communication capabilities to customers. Such networks are a desirable choice for delivering high-speed communication data because they can avoid the use of active electronic devices, such as amplifiers and repeaters, between a central office and a subscriber termination. The absence of active electronic devices may decrease network complexity and/or cost and may increase network reliability.

As networks become increasingly complex, however, the need for management of the optical signals becomes increasingly important. Many optical signal management functions, such as redirecting signals to bypass a faulty component, or opening new channels as more users are added to the network, can be accomplished using active optical switches, such as electro-wetting on dielectric (EWOD)-activated optical switches. An important consideration for designing and implementing optical circuits for the management of optical signals is that the switch devices operate with high performance, i.e. have high optical transmission of the incoming signal into the desired output channel and low optical transmission into the other output channel. In general, higher performance optical switches require a larger footprint in the optical circuit than low performance switches. The space available on the substrate of the optical chip, however, may be limited, e.g. because of manufacturing limits on substrate size.

Therefore, there is a need to develop an optical switch network architecture that permits an increased density of high performance optical switches on the optical chip, so that performance and complexity of optical management capabilities can both be high.

Summary of the Invention

One embodiment of the invention is directed to an optical switching device that has electro-wetting on dielectric (EWOD)- actuated optical switches on a substrate. The optical switches are arranged in a plurality of rows and interconnected via interconnecting waveguides, comprising at least a first row of optical switches and a second row of optical switches. One or more input waveguides are coupled to respective one or more optical switches of the optical switch network. One or more output waveguides are coupled to respective one or more optical switches of the optical network. A microchannel network, for distributing droplets of electro-wetting liquid to the optical switches, has a first microchannel disposed proximate the first row of optical switches for distributing droplets of electro-wetting liquid to the optical switches of the first row of optical switches and a second microchannel disposed proximate the second row of optical switches for distributing droplets of electro-wetting liquid to the optical switches of the second row of optical switches.

Another embodiment of the invention is directed to an optical switching device that includes an optical switch network having electro-wetting on dielectric (EWOD)-actuated optical switches on a substrate. The optical switches are arranged in at least a first row of optical switches. A microchannel network for distributing droplets of electro-wetting liquid to the optical switches, has a first microchannel disposed proximate the first row of optical switches. No more than one than one droplet of electro-wetting liquid is moveable along the first microchannel to address the optical switches in the first row of optical switches.

Another embodiment of the invention is directed to an optical switching device that has an optical switch network that includes electro-wetting on dielectric (EWOD)-actuated optical switches on a substrate wetting liquid to the optical switches of the first column of optical switches and a second microchannel disposed proximate the second column of optical switches for distributing droplets of electro-wetting liquid to the optical switches of the second row of optical switches.

Another embodiment of the invention is directed to an optical switching device that includes an optical switch network having electro-wetting on dielectric (EWOD)-actuated optical switches on a substrate. The optical switches are arranged in at least a first column of optical switches. A microchannel network distributes droplets of electro-wetting liquid to the optical switches. The microchannel network comprises a first microchannel disposed proximate the first column of optical switches. There is no more than one droplet of electro-wetting liquid in the first microchannel, the one droplet of electro-wetting liquid being movable between the optical switches in the first column of optical switches.

Brief Description of the Drawings

The invention may be more completely understood in consideration of the following detailed description of various embodiments of the invention in connection with the accompanying drawings, in which:

FIG. 1 schematically illustrates an embodiment of a waveguide optical switch according to an embodiment of the present invention;

FIG. 2A schematically illustrates a cross-sectional view through waveguide optical switch according to an embodiment of the invention;

FIG. 2B illustrates operation of a waveguide optical switch in a bar state, according to an embodiment of the invention;

FIG. 2C illustrates operation of a waveguide optical switch in a cross state, according to an embodiment of the invention;

FIG. 3 illustrates principles of electro-wetting as used in an EWOD-activated optical switch;

FIG. 4 schematically illustrates an embodiment of an EWOD-activated optical switch network as may be used in an optical chip according to the present invention;

FIG. 5 schematically illustrates an embodiment of a microchannel network as may be used in an optical chip according to the present invention;

FIG. 6 schematically illustrates an embodiment of an optical chip that includes the EWOD-activated optical switch network and microchannel network of FIGs. 4 and 5, according to the present invention;

FIG. 7 schematically illustrates another embodiment of a microchannel network as may be used in an optical chip according to the present invention; and

FIG. 8 schematically illustrates another embodiment of an optical chip that includes the EWOD-activated optical switch network and microchannel network of FIGs. 4 and 7, according to the present invention.

While the invention is amenable to various modifications and alternative forms, specifics thereof have been shown by way of example in the drawings and will be described in detail. It should be understood, however, that the intention is not to limit the invention to the particular embodiments described. On the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

Detailed Description

The present invention is directed to various optical devices and systems that can provide benefit in optical networks. In particular, the invention is directed to integrated optical switching devices capable of operating over an extended bandwidth that permits signals of multiple functionalities to be transmitted over, and controlled within, a fiber network.

FIG. 1 schematically illustrates an embodiment of an integrated optical switch 100. The optical switch 100 incorporates a first waveguide 102 and a second waveguide 104. The first and second waveguides 102, 104 are physically close to one another in a coupling region 106, a region in space where light propagating along one of the waveguides 102, 104 may couple to the other waveguide 104, 102. Whether light couples between the waveguides 102, 104 depends on the effective refractive index experienced by the light as it propagates along the waveguides 102, 104. The effective refractive index can be altered by positioning a fluid of greater or lesser refractive index close to the coupling region 106.

The figure shows two droplets of liquid. A first droplet 108 is positioned over the coupling region 106 and a second droplet 110 is positioned to the side of the coupling region 106. The first droplet 108 has a first refractive index and the second droplet 110 has a second refractive index, different from the first refractive index. A microfluidic channel may be used for controlling the positions of the first and second droplets 108, 110 relative to the coupling region 106. In the illustrated embodiment, an optical signal transmitted into the first waveguide

102 is output from the first waveguide 102 when the first droplet 108 is over the coupling region 106. This is referred to as the switch's "bar state." The optical signal is output from the second waveguide 104 when the second droplet 110 is positioned over the coupling region 106. This is referred to as the switch's "cross state." Microfluidic optical switches have previously been described, for example in U.S. Provisional Patent Application No. 62/094,506, "Integrated Optical Switching and Splitting for Optical Networks," filed on December 19, 2014, in U.S. Provisional Patent Application No. 62/116,784, entitled "Remote Control and Power Supply for Optical Networks," filed on February 16, 2015, and in WO 2015/092964A1, "Adiabatic Coupler," published on June 25, 2015, all of which are incorporated herein by reference.

A cross-section through a microfluidic optical waveguide switch is schematically illustrated in FIG. 2A. In this embodiment, the substrate 200 contains the first waveguide 202 and the second waveguide 204. An etched region 206 above the second waveguide 204 exposes the second waveguide 204 at or close to the upper surface 208 of the substrate 200. The first waveguide 202 remains buried below the upper surface 208 of the substrate 200. In the illustration, the droplet 212 of the second liquid is positioned above the etched region 206, so that the refractive index of the second liquid 212 affects the effective refractive index experienced by light propagating along the second waveguide 204. According to the illustrated embodiment, light can couple between the first and second waveguides 202, 204 when the droplet 212 of the second liquid is in the etched region 206. In other words, the switch is in the cross state.

When the droplet 210 of the first liquid is moved over the etched region, the effective refractive index experienced by the light propagating along the waveguide 204 is changed, preventing coupling of light between the waveguides 202, 204, and the switch is in the bar state.

FIGs. 2B and FIG. 2C illustrate how light is coupled between waveguides in the type of optical switch described above. FIG. 2B illustrates the switch in the bar state, when a liquid of relatively low refractive index is positioned above the etched region. The graph shows a plot of effective propagation constant, β_{eff}, as a function of position, z, along the coupling region. The flat line, labeled, waveguide A, illustrates the effective propagation constant for the waveguide along which the light is propagating and the sloped line (waveguide B) illustrates the effective propagation constant for the other waveguide. Since there is a gap between the effective propagation constants, light does not couple from one waveguide to the other. This is seen in the pictures to the right of the graph, where light entering the switch on the first waveguide 202 remains on the first waveguide (upper picture) and light entering the switch on the lower waveguide 204 remains in the lower waveguide (lower picture).

FIG. 2C illustrates the situation with the switch in the cross state. In this case, the graph shows the effective propagation constant of the other waveguide crosses that of the waveguide along which the light is propagating, allowing light to propagate between the two waveguides. This is seen in the pictures to the right of the graph, in which the light entering the switch on the first waveguide 202 exits the switch on the second waveguide 204 (upper picture) and light entering the switch on the second waveguide 204 exits the switch on the first waveguide 202 (lower picture).

A microfluidic approach to moving the optical liquids relative to the waveguides, using the technique of electro-wetting, is schematically illustrated in FIG. 3. A liquid droplet 302 is disposed within a microchannel 304 formed between two walls 306, 308. The first wall 306 is provided with a common electrode 310, insulated from the channel 304 by a first dielectric layer 312 which provides electrical insulation between the common electrode 310 and the liquid droplet 302. A first hydrophobic layer 314 may be deposited over the first dielectric layer 312.

The second wall 308 is provided with a number of electrodes 316 that can be activated with an applied voltage independently of each other. In the illustrated embodiment, there are two independently addressable electrodes 316a, 316b, but it will be appreciated that other embodiments of the invention may include a larger number of addressable electrodes 316. A second dielectric layer 318 insulates the electrodes 316a, 316b from the channel 304. A hydrophobic layer 320 may be deposited over the second dielectric layer 318.

The electro-wetting (EW) effect can be described as a change in the contact angle of the liquid due to an applied potential difference between the liquid and the channel wall. Thus, when a potential is applied to one of the electrodes 316, the surface tension of the droplet can be reduced, allowing it to "wet" the channel wall 308 in the direction toward the electrode 316 across which the potential is applied. Since the EW effect is applied to a liquid droplet 302 separated from the electrode by a dielectric layer, this particular configuration is referred to a EW on dielectric (EWOD).

In FIG. 3a, the liquid droplet 302 is above the first addressable electrode 316a. The graph below the channel cross-section shows the voltages applied to the common electrode, Vc, the voltage applied to the first addressable electrode 316a, Va, and the voltage applied to the second addressable electrode, Vb. In FIG. 3a, there is no voltage applied to any electrode. In FIG. 3b, voltages are applied sequentially to the second addressable electrode 316b and to the common electrode 310 and the first addressable electrode 316a, which results in movement of the droplet 302 to a position over the second addressable electrode 316b, as shown in FIG. 3c. Thus, the selective application of electrical potentials to the electrodes of the electro-wetting device can result in a desired movement of the EW liquid droplet 302. The use of the EW effect to move liquid droplets is well known, and the use of microfluidics in the control of optical waveguide devices has been described in WO2015/092064A1, "Adiabatic Coupler," filed on December 21, 2014, incorporated herein by reference, in U.S. Provisional Patent Application No. 62/094,506, "Integrated Optical Switching and Splitting for Optical Networks," filed on December 19, 2014, and in U.S. Provisional Patent Application No. 62/116,784, entitled "Remote Control and Power Supply for Optical Networks," filed on February 16, 2015, both of which have been incorporated by reference. Of course, it will be appreciated that other conformations and configurations of electrode and liquid can be used to move the droplets 302.

Such an approach may also be used to move two or more liquids. For example, if a channel contains two immiscible liquids, separated at an inter-liquid interface, movement of one of the liquids via an EW force can result in both liquids being moved along the channel. One advantage of this technique is that the second liquid can be moved along the channel by the EW forces acting on the first liquid, even though the second liquid itself does not exhibit EW behavior, or only responds weakly to an EW control signal. For example, EW liquids are typically polar in nature, but the second liquid may be nonpolar.

Additionally, an EW technique can be used to move a droplet of an electro-wetting liquid around a network of microchannels, so long as electrodes are suitably positioned along the different channels. In illustration, such an arrangement may be used to move an EW liquid droplet between different locations in an EWOD-activated optical switch array, for example between different optical switches. Also, an EW approach may be used to move EW droplets from a reservoir of EW liquid to selected positions in the EWOD-activated optical switch array.

The design of an EWOD-actuated optical switch includes various considerations, including some that may appear to be contradictory of each other. On one hand, it is important that each optical switch in a switch array operates with high efficiency and low loss. For adiabatic coupler switches using a high index difference waveguide, such as silicon or silicon nitride in silicon dioxide, such as is exemplified in FIGs. 1 and 2A-2D, a coupler length of around 1400 μm gives acceptable performance over the wavelength range of around 1260 nm to about 1650 nm. In this case, acceptable performance means that losses for light in the desired waveguide ("the bright waveguide") are less than about 1 dB, while losses in the other waveguide ("the dark waveguide") are greater than about 10 dB, preferably greater than about 25 dB, and more preferably greater than about 30 dB. Shorter EWOD-activated coupler switches are less effective. For example, when the coupler length is reduced to about 630 μm from 1400 μm, the losses in the bright waveguide can fall to around 4-5 dB, while the losses in the dark waveguide may be only around 3-10 dB. Accordingly, the longer coupler switch gives a more desirable performance. On the other hand, longer EWOD-activated coupler switches use more space on the substrate on which the optical chip is manufactured.

One approach to increasing the number of EWOD-activated coupler switches on a substrate 400 is schematically illustrated in FIG. 4. The substrate contains a switching network 402 formed using a number of EWOD-activated coupler switches 404, input waveguides 406, interconnecting waveguides 408 and 410 and output waveguides 412 and 414. In some situations, output waveguides 412 may be used for test purposes with output waveguides 414 being used as device outputs. The switches 404 are coupled together using interconnecting waveguides 408 and 410 to form a switching network 402 configured as a cross-bar network. In this type of network, the switches 404 are arranged in rows and columns. There are two types of interconnecting waveguides, *viz.* the row interconnecting waveguides 408 that connect from the output of one switch 404 to the input of an adjacent switch 404 in the same row, but a different column, and the column interconnecting waveguides 410 that connect from the output of one switch 404 to the input of an adjacent switch in the same column, but different row.

For purposes of this description, the rows are designated with the upper case capital alphabetic characters, A, B, C, D, while the columns are designated with lower case alphabetic characters a, b, c, d. Accordingly, the switches 404, input waveguides 406, interconnecting waveguides 408 and 410 and output waveguides 414 may be designated according to their row and column in the network. For example the input waveguide 406 on the third row down, row C, is designated input waveguide 406C. The switch on the third row down, row C, and the second column across, column b, is designated switch 404Cb. The row interconnecting waveguide 408 on the third row, row C, that connects from the second switch in the row, switch 404Cb, to the third switch in the row, switch 404Cc, may be referred to as row interconnecting waveguide 408Cb. The column interconnecting waveguide 410 on the second column, column b, that connects from the third switch in the column, switch 404Cb, to the fourth switch in the column, switch 404Db, may be referred to as column interconnecting waveguide 410Cb. The output waveguide 412 on the third row down, row C, may be designated as test waveguide 412C, while the output waveguide on the second column, column b, is designated as output waveguide 414b.

The illustrated embodiment of cross-bar network is in a 4 x 4 arrangement, with four rows and four columns, but it will be understood that other sizes of network may also be used, such as an 8 x 8 or 16 x 16 network. In addition, the network need not be square, but may have more rows than columns of vice versa, for example 4 x 8 or 8 x 4.

In the illustrated embodiment, the input waveguides 406 are coupled to the lower inputs of the switches 404 in column a. If all the switches 404 are in the bar state without the presence of a liquid droplet, then the signal input at input waveguide 406D appears as an output at output waveguide 414a. Also, the signal input at input waveguide 406C appears as an output signal at output waveguide 414b, the signal input at input waveguide 406B appears as an output signal at output waveguide 414c, and the signal input at input waveguide 406A appears as an output signal at output waveguide 414d.

Table 1: Correlation Between Input and Output for the Switch Array of FIG. 4 When no More Than One Column A Switch is in the Cross State

	Outputs when the listed switch is in the cross state				
Input	None	404Aa	404Ba	404Ca	404Da
406A	414d	412D	414c	414d	414d
406B	414c	414c	414d	414b	414c
406C	414b	414b	414b	414c	414a

406D	414a	414a	414a	414a	414b

Table 2 shows how the various input signals are correlated to various outputs when all the switches in the array are in the bar state except one switch in column b.

Table 2: Correlation Between Input and Output for the Switch Array of FIG. 4 When no More Than One Column B Switch is in the Cross State

	Outputs when the listed switch is in the cross state				
Input	None	404Ab	404Bb	404Cb	404Db
406A	414d	414d	412D	414c	414d
406B	414c	414c	414c	414d	414b
406C	414b	414b	414b	414b	414c
406D	414a	414a	414a	414a	414a

Other correlations are available when additional switches are set in the cross state, but are not all presented here.

This arrangement permits a certain amount of redundancy, as illustrated by comparing the correlations between inputs and outputs in the two tables. The correlations are the same when switch 404Aa is in the cross state as when switch 404Bb is in the cross state. Thus, various input/output correlations may be achieved using different switch configurations. This is useful if, for example, a switch fails – the array 402 can be reconfigured to achieve the same input/output correlation as was used before the switch failure. Thus, switching may occur, for example from 404Aa to 404Bb so as to maintain the same output signals, without interrupting the service of the input signals at 406C and 406D.

In other embodiments, each optical switch 404 is in the cross state unless the liquid droplet activates it into the bar state. In these embodiments, when there is only one droplet per column, the position droplet determines which output waveguide 406 is connected to which output waveguide 414. For example, if a droplet is located at optical switch 404Ac, resulting in optical switch 404Ac being in the bar state, then the signal input at waveguide 406A is connected to output waveguide 414c. Likewise, if there is a droplet located at optical switch 404Dd, then optical switch 404Dd is in the bar state, and the signal input at waveguide 406D is connected to output waveguide 414D. One example of the switch array configuration for this embodiment is shown in Table 3 below.

Table 3: Correlation Between Input and Output for the Switch Array of FIG. 4 When the Listed Switch is in the Bar State

Outputs when the listed switch is in the bar state				
Input	404Aa	404Bb	404Cc	404Dd
406A	414a			
406B		414b		
406C			414c	
406D				414b

It will be appreciated that other configurations are possible. So long as there is only one switch per column in the bar state, then there is a unique, one-to-one correspondence between the input waveguides 406 and the output waveguides 414, where the output column for a particular input row is set by the switch that lies at the intersection of that row and column. Another possible configuration of the switch array in this embodiment is shown in Table 4.

Table 4: Correlation Between Input and Output for the Switch Array of FIG. 4 When the Listed Switch is in the Bar State

Outputs when the listed switch is in the bar state				
Input	404Ba	404Ab	404Dc	404Cd
406A		414b		
406B	414a			
406C				414d
406D			414c	

Additional input/output correlations are available when more than one switch is in the cross state, and it has been found that an arrangement where up to one switch per row can be a switched is a useful arrangement. One embodiment a microchannel network 500 that might be used to activate a switch network 402 is schematically illustrated in FIG. 5. The microchannel network 500 is formed on the substrate 400, preferably over the switch network in a manner like that shown in FIGs. 2 and 3. A reservoir 502 is provided as a store for the electro-wetting liquid. A main microchannel 504 leads from the reservoir 502 to row microchannels 506, where each microchannel 506 is associated with a respective row of EWOD-activated optical switches 404. Each row microchannel 506 is provided with a number of access channels 508 that permit the droplet of electro-wetting liquid access to the region above respective optical switches 404. In some embodiments, the EW liquid is used along with a second liquid, and an escape channel (not shown) may be provided between an access channel 508 and a row microchannel 506 to permit the second liquid to flow out of the access channel 508 when the EW liquid droplet enters the access channel 508. A system of electrodes, not shown, may be used to bud a droplet of the electro-wetting liquid from the reservoir 502 and deliver it via the main microchannel 504 and a selected row microchannel 506 and access microchannel 508 to a selected optical switch 404. When a droplet 510 has been delivered via an access channel 508 to a selected optical switch

404, in a specific row, the droplet may be backed out from the access channel 508 to the row microchannel 506 and delivered via electro-wetting forces to another access channel 508 in the same row. In an illustrative example, the figure shows a droplet 510 (solid line) at access channel 508Cb, corresponding to optical switch 404Cb. By selective application of specific voltages to the electrodes of the microchannel network 500, the droplet 510 may be moved to another access channel 508, such as access channel 508Cd, (where the droplet 510 is illustrated in dashed lines).

FIG. 6 schematically illustrates the microchannel network 500 (solid lines) overlying the EWOD-activated optical switch network 402 (dashed lines), showing how the various access channels correlate with their respective optical switches.

Another embodiment of the invention is described with reference to FIGs. 7 and 8. The microchannel network 700 is formed on the substrate 400, preferably over the switch network in a manner like that shown in FIGs. 2 and 3. A reservoir 702 is provided as a store for the electro-wetting liquid. A main microchannel 704 leads from the reservoir 702 to column microchannels 706, where each column microchannel 706 is associated with a respective column of the array of EWOD-activated optical switches 404. Each column microchannel 706 is provided with a number of access channels 708 that permit the droplet of electro-wetting liquid access to the region above respective optical switches 404. In some embodiments, the EW liquid is used along with a second liquid, and an escape channel (not shown) may be provided between an access channel 708 and a column microchannel 706 to permit the second liquid to flow out of the access channel 708 when the EW liquid droplet enters the access channel 708.

A system of electrodes, not shown, may be used to bud a droplet of the electro-wetting liquid from the reservoir 702 and deliver it via the main microchannel 704 and a selected column microchannel 706 and access microchannel 708 to a selected optical switch 404. When a droplet 710 has been delivered via an access channel 708 to a selected optical switch 404, in a specific column, the droplet may be backed out from the access channel 708 to the column microchannel 506 and delivered via electro-wetting forces to another access channel 708 in the same row. In an illustrative example, the figure shows a droplet 710 (solid line) at access channel 708Ac, corresponding to optical switch 404Ac. By selective application of specific voltages to the electrodes of the microchannel network 700, the droplet 710 may be moved to another access channel 708 on the same column microchannel 706, such as access channel 708Cc (where the droplet 710 is illustrated in dashed lines).

FIG. 8 schematically illustrates the microchannel network 700 (solid lines) overlying the EWOD-activated optical switch network 402 (dashed lines), showing how the various access channels correlate with their respective optical switches 40.

While the use of access channels 508, 708 is not a requirement for the invention, it is advantageous to be able transport a droplet 510, 710 along a row or column microchannel 506. 706 without letting it pass over an optical switch 404 whose switching state is not intended to be changed, even for the short time it takes to move the droplet 510, 710 past the switch 404 to the droplet's destination.

As has been discussed above, the invention is not limited to the 4 x 4 switch network illustrated in the accompanying figures, but may be adapted to different sizes of switch network. The current invention is particularly useful for increasing the density of high performance EWOD optical switches on the substrate, and providing for a versatile, adaptable switch array. In particular, for a silicon substrate having a dimension of 25.6 mm x 27.5 mm, the EWOD switch array may be as large as 16 x 16. The optical switch network of the present invention permits the switching of one or more input signals to different respective outputs, without interrupting the service of other input signals. For example, the outputs associated with inputs 406A and 406B could be swapped from 414a and 414b respectively to 414b and 414a respectively, without altering the flow of the signals from inputs 406C or 406D. Furthermore, only one droplet is needed for each row and each column to uniquely couple each input 406 to each output 414.

As noted above, the present invention is applicable to fiber optical communication and data transmission systems. Accordingly, the present invention should not be considered limited to the particular examples described above, but rather should be understood to cover all aspects of the invention as fairly set out in the attached claims. Various modifications, equivalent processes, as well as numerous structures to which the present invention may be applicable will be readily apparent to those of skill in the art to which the present invention is directed upon review of the present specification. The claims are intended to cover such modifications and devices.

What is claimed is:

1. An optical switching device, comprising:

an optical switch network comprising electro-wetting on dielectric (EWOD)- actuated optical switches on a substrate, the optical switches being arranged in a plurality of rows and interconnected via interconnecting waveguides, comprising at least a first row of optical switches and a second row of optical switches;

one or more input waveguides coupled to respective one or more optical switches of the optical switch network;

one or more output waveguides coupled to respective one or more optical switches of the optical network;

a microchannel network for distributing droplets of electro-wetting liquid to the optical switches, the microchannel network comprising a first microchannel disposed proximate the first row of optical switches for distributing droplets of electro-wetting liquid to the optical switches of the first row of optical switches and a second microchannel disposed proximate the second row of optical switches for distributing droplets of electro-wetting liquid to the optical switches of the second row of optical switches.

2. A device according to claim 1, wherein the optical switch network is configured as a cross-bar network, with row interconnecting waveguides connecting between respective optical switches and adjacent optical switches within the rows.

3. A device according to claim 2, wherein the optical switches are further arranged in columns, and comprising column interconnecting waveguides connecting between respective optical switches and adjacent optical switches within the columns.

4. A device according to claim 1, wherein the first microchannel contains only one droplet of electro-wetting liquid for activating the optical switches in the first row.

5. A device according to claim 4, wherein the second microchannel contains only one droplet of electro-wetting liquid for activating the optical switches in the second row.

6. A device according to claim 1, wherein the optical switch network comprises at least four input waveguides and at least four output waveguides.

7. A device according to claim 1, wherein the optical switch network comprises sixteen rows of optical switches and sixteen columns of optical switches, and wherein the optical switches each have a transmission loss of less than 1 dB into a desired switch output.

8. A device according to claim 1, further comprising a reservoir for electro-wetting liquid coupled to the microchannel network.

9. A device according to claim 1, wherein the first microchannel has an elongated portion located transverse to the first row of optical switches and the microchannel network further comprises access microchannels coupled to the first microchannel, each access microchannel being positioned to receive a droplet of electro-wetting liquid over a respective optical switch.

10. An optical switching device, comprising:

an optical switch network comprising electro-wetting on dielectric (EWOD)-actuated optical switches on a substrate, the optical switches being arranged in at least a first row of optical switches;

a microchannel network for distributing droplets of electro-wetting liquid to the optical switches, the microchannel network comprising a first microchannel disposed proximate the first row of optical switches; and

no more than one droplet of electro-wetting liquid in the first microchannel, the no more than one droplet of electro-wetting liquid being movable between the optical switches in the first row of optical switches.

11. A device according to claim 10, wherein the switches in the first row of optical switches are interconnected with row interconnecting waveguides between respective optical switches and adjacent optical switches within the first row of optical switches.

12. A device according to claim 10, wherein the optical switches are further arranged in at least a second row of optical switches, and wherein the microchannel network further comprises a second microchannel disposed proximate the second row of optical switches, wherein the second microchannel contains no more than one droplet of electro-wetting liquid movable between the optical switches in the second row of optical switches.

13. A device according to claim 12, wherein the optical switch network is a cross-bar network comprising optical switches arranged in columns, comprising row interconnecting waveguides connecting between respective switches and adjacent switches within the rows of optical switches and column interconnecting waveguides connecting between respective switches and adjacent switches within the columns of optical switches.

14. A device according to claim 10, further comprising one or more input waveguides coupled to respective one or more optical switches of the optical switch network and one or more output waveguides coupled to respective one or more optical switches of the optical network.

15. A device according to claim 10, wherein the optical switch network comprises sixteen rows of optical switches and sixteen columns of optical switches, and wherein the optical switches each have a transmission loss of less than 1 dB into a desired switch output.

16. A device according to claim 10, further comprising a reservoir for electro-wetting liquid coupled to the microchannel network.

17. A device according to claim 10, wherein the first microchannel has an elongated portion located transverse to the first row of optical switches and further comprises access microchannels, each access microchannel being positioned to receive a droplet of electro-wetting liquid over a respective optical switch of the first row of optical switches.

18. An optical switching device, comprising:

an optical switch network comprising electro-wetting on dielectric (EWOD) actuated optical switches on a substrate, the optical switches being arranged in a plurality of columns and interconnected via interconnecting waveguides, comprising at least a first column of optical switches and a second column of optical switches;

one or more input waveguides coupled to respective one or more optical switches of the optical switch network;

one or more output waveguides coupled to respective one or more optical switches of the optical network;

a microchannel network for distributing droplets of electro-wetting liquid to the optical switches, the microchannel network comprising a first microchannel disposed proximate the first row of optical switches for distributing droplets of electro-wetting liquid to the optical switches of the first column of optical switches and a second microchannel disposed proximate the second column of optical switches for distributing droplets of electro-wetting liquid to the optical switches of the second row of optical switches.

19. A device according to claim 18, wherein the optical switch network is configured as a cross-bar network, with column interconnecting waveguides connecting between respective optical switches and adjacent optical switches within the columns.

20. A device according to claim 19, wherein the optical switches are further arranged in rows, and comprising row interconnecting waveguides connecting between respective optical switches and adjacent optical switches within the rows.

21. A device according to claim 18, wherein the first microchannel contains only one droplet of electro-wetting liquid for activating the optical switches in the first column.

22. A device according to claim 21, wherein the second microchannel contains only one droplet of electro-wetting liquid for activating the optical switches in the second column.

23. A device according to claim 18, wherein the optical switch network comprises at least four input waveguides and at least four output waveguides.

24. A device according to claim 18, wherein the optical switch network comprises sixteen rows of optical switches and sixteen columns of optical switches, and wherein the optical switches each have a transmission loss of less than 1 dB into a desired switch output.

25. A device according to claim 18, further comprising a reservoir for electro-wetting liquid coupled to the microchannel network.

26. A device according to claim 18, wherein the first microchannel includes an elongated portion located transverse to the first row of optical switches and further comprises access microchannels coupled to the first microchannel, each access microchannel being positioned to receive a droplet of electro-wetting liquid over a respective optical switch.

27. An optical switching device, comprising:

an optical switch network comprising electro-wetting on dielectric (EWOD)-actuated optical switches on a substrate, the optical switches being arranged in at least a first column of optical switches;

a microchannel network for distributing droplets of electro-wetting liquid to the optical switches, the microchannel network comprising a first microchannel disposed proximate the first column of optical switches; and

no more than one droplet of electro-wetting liquid in the first microchannel, the no more than one droplet of electro-wetting liquid being movable between the optical switches in the first column of optical switches.

28. A device according to claim 27, wherein the switches in the first column of optical switches are interconnected with column interconnecting waveguides between respective optical switches and adjacent optical switches within the first column of optical switches.

29. A device according to claim 27, wherein the optical switches are further arranged in at least a second column of optical switches, and wherein the microchannel network further comprises a second microchannel disposed proximate the second column of optical switches,

wherein the second microchannel contains no more than one droplet of electro-wetting liquid movable between the optical switches in the second column of optical switches.

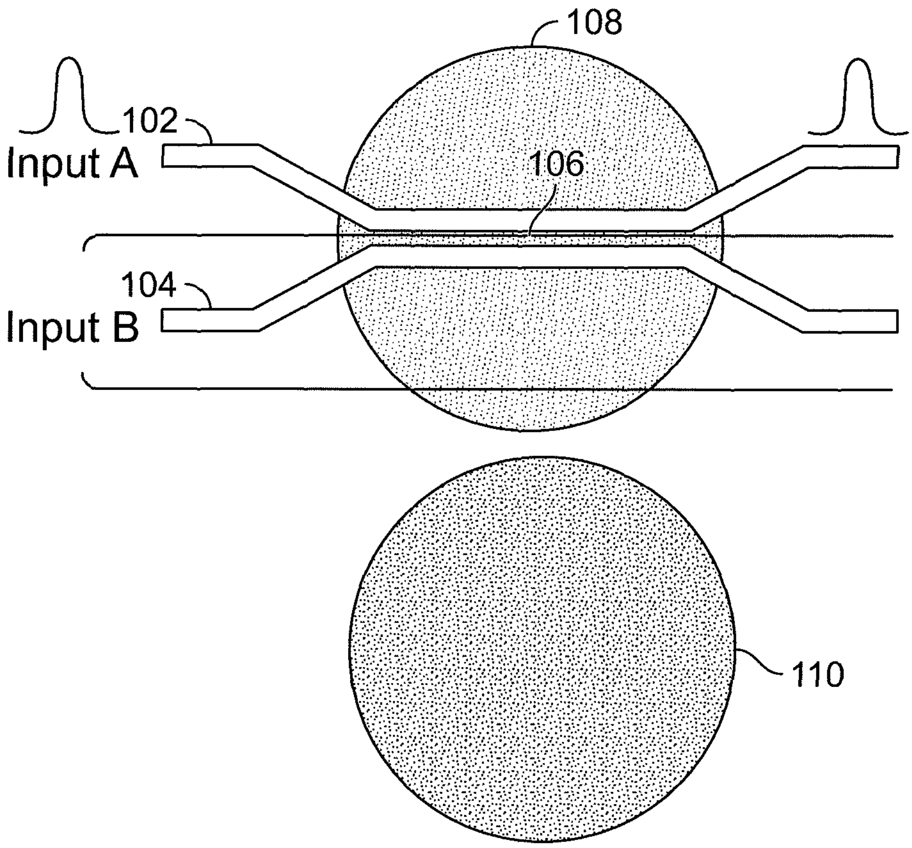
30. A device according to claim 29, wherein the optical switch network is a cross-bar network comprising optical switches arranged in rows, comprising row interconnecting waveguides connecting between respective switches and adjacent switches within the rows of optical switches and column interconnecting waveguides connecting between respective switches and adjacent switches within the at least a first column of optical switches.

31. A device according to claim 27, further comprising one or more input waveguides coupled to respective one or more optical switches of the optical switch network and one or more output waveguides coupled to respective one or more optical switches of the optical network.

32. A device according to claim 27, wherein the optical switch network comprises sixteen rows of optical switches and sixteen columns of optical switches, and wherein the optical switches each have a transmission loss of less than 1 dB into a desired switch output.

33. A device according to claim 27, further comprising a reservoir for electro-wetting liquid coupled to the microchannel network.

34. A device according to claim 27, wherein the first microchannel has an elongated portion located transverse to the first column of optical switches and further comprises access microchannels, each access microchannel being positioned to receive a droplet of electro-wetting liquid over a respective optical switch of the first column of optical switches.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102
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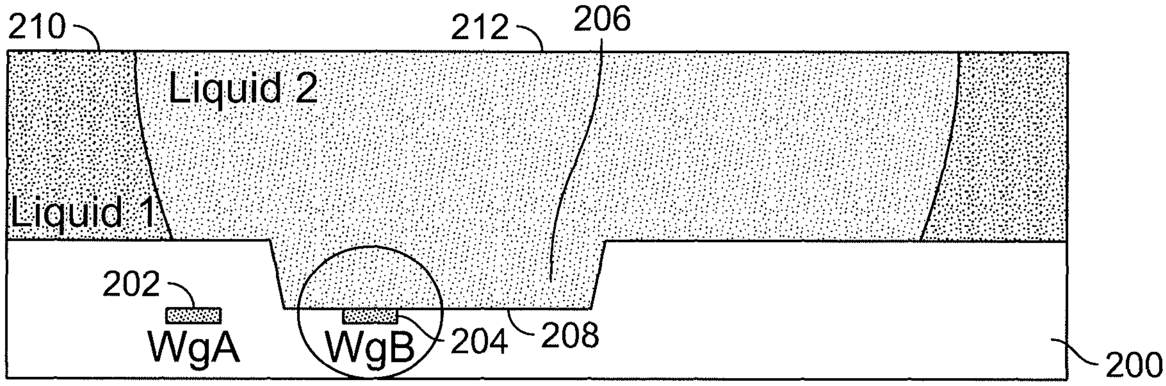
106
104
Input B
110

FIG. 1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212
206
Liquid 2
Liquid 1
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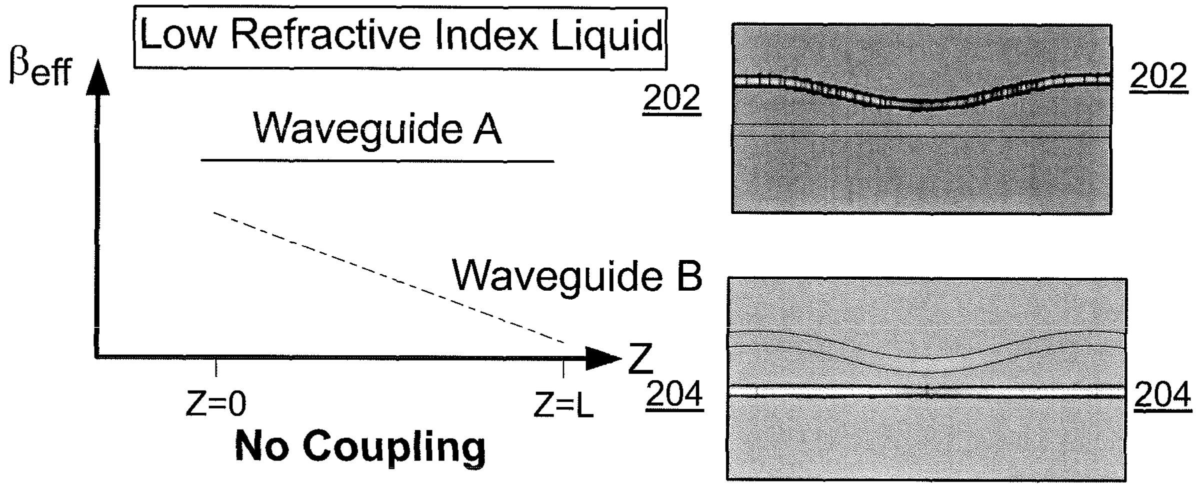
208
200

FIG. 2A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Waveguide B
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Z=L
No Coupling
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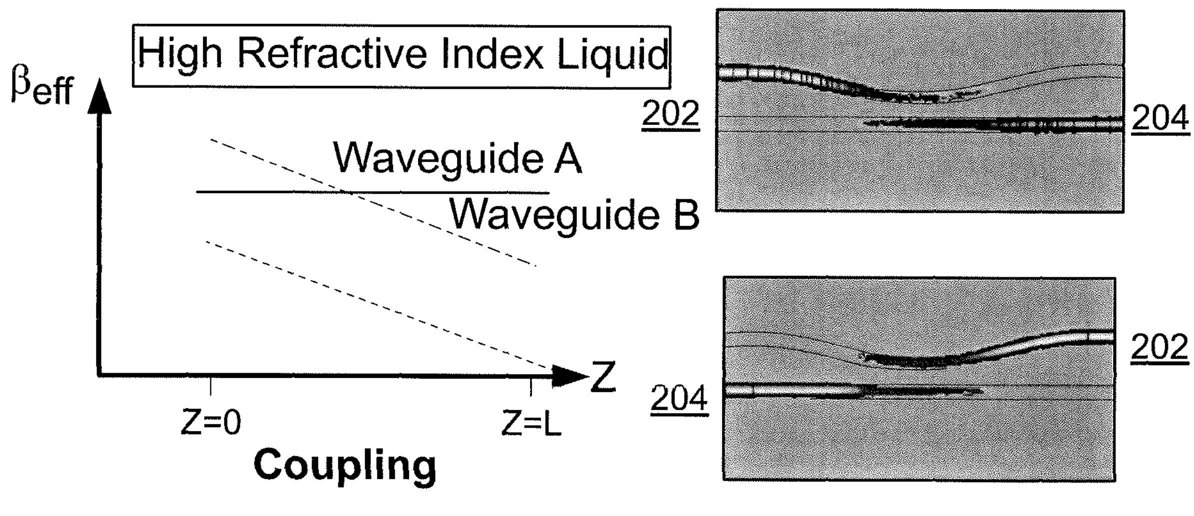
204

FIG. 2B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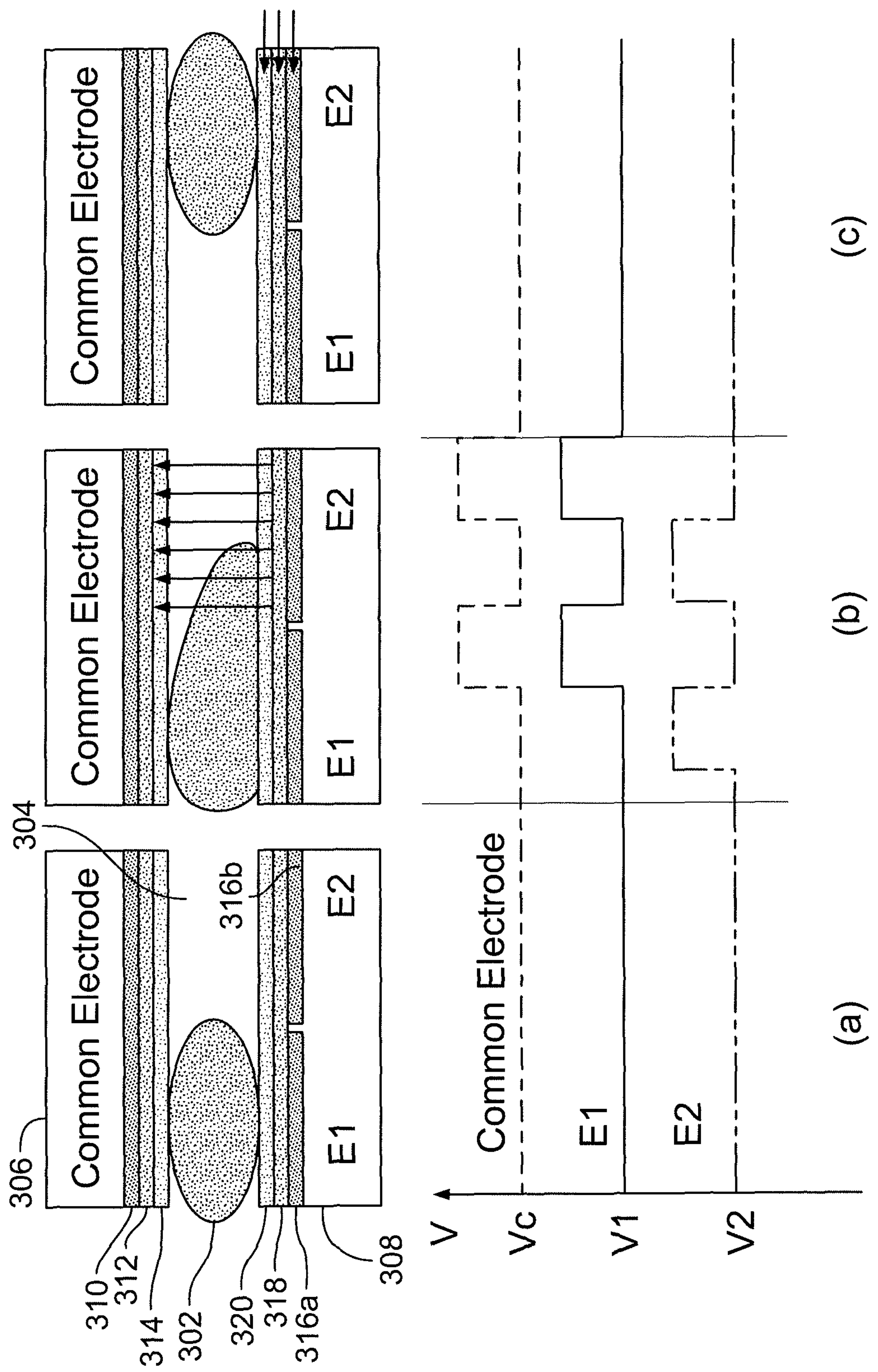
β_{eff}
Waveguide A
Waveguide B
Z
Z=0
Z=L
Coupling
202
204
202
204

FIG. 2C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316b
E1
E2
310
312
314
302
320
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316a
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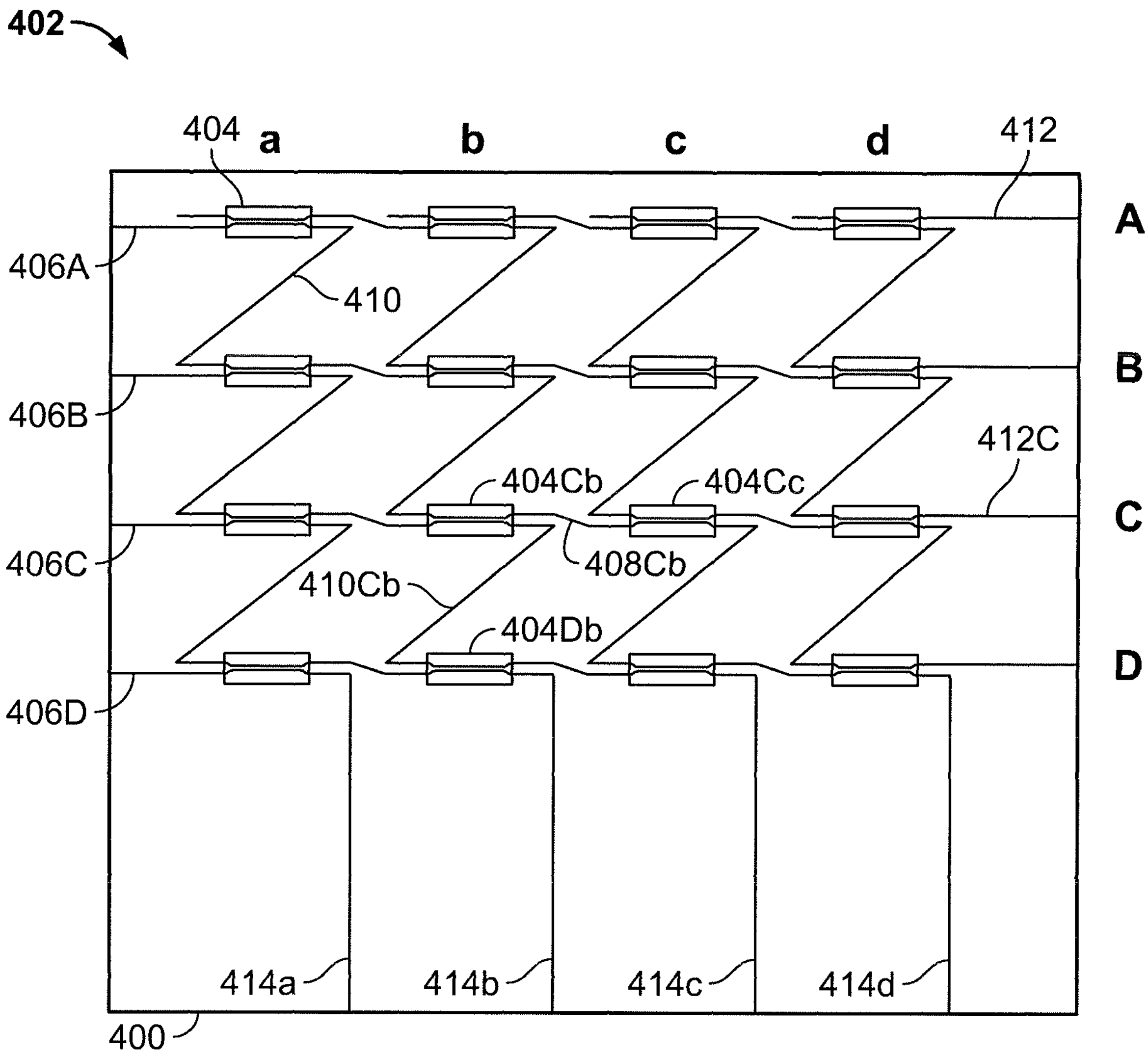
V
Vc
V1
V2
Common Electrode
E1
E2
(a)
(b)
(c)

FIG. 3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a
b
c
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412
A
B
C
D
406A
410
406B
412C
404Cb
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414c
414d
400

FIG. 4

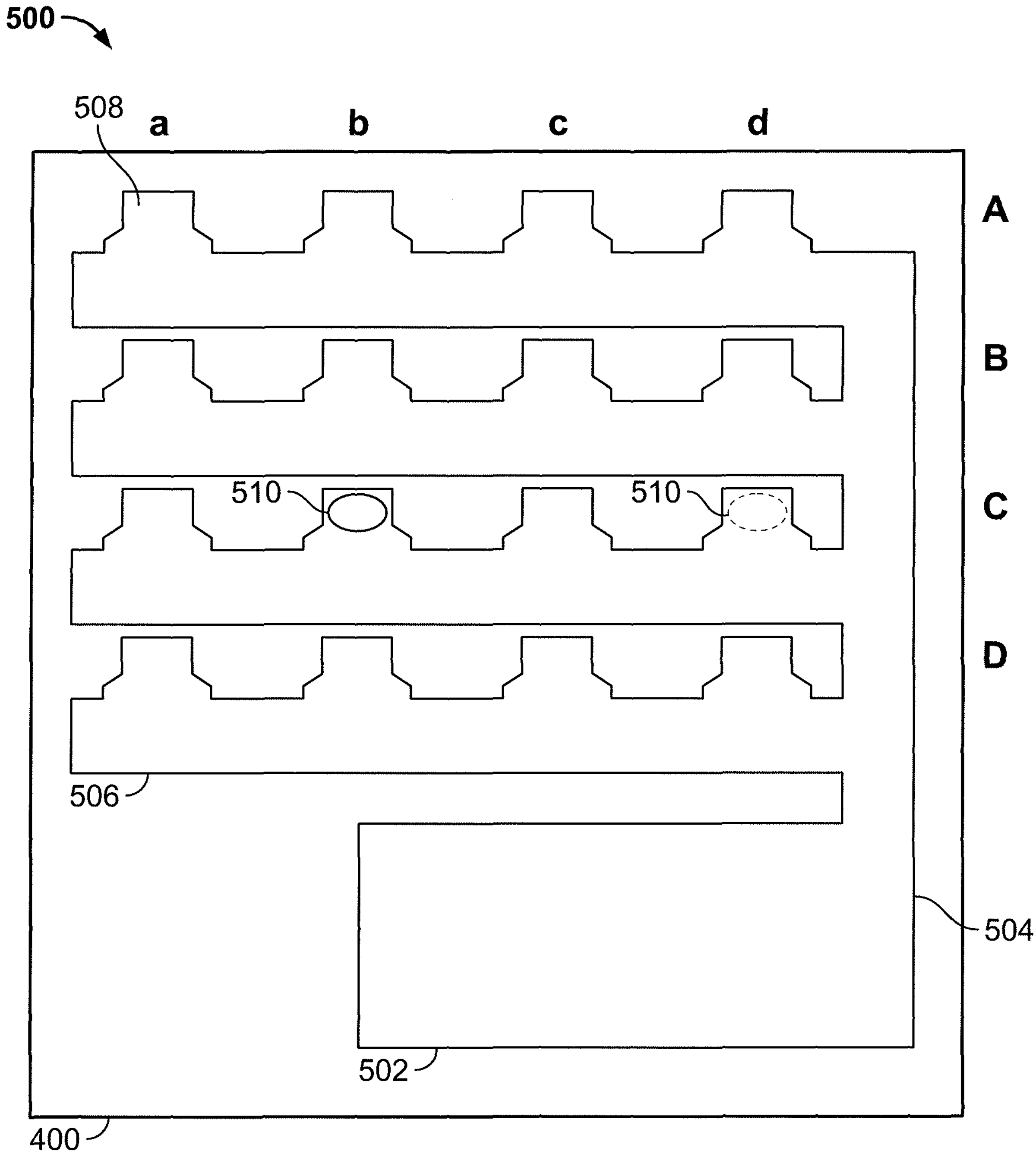

FIG. 5

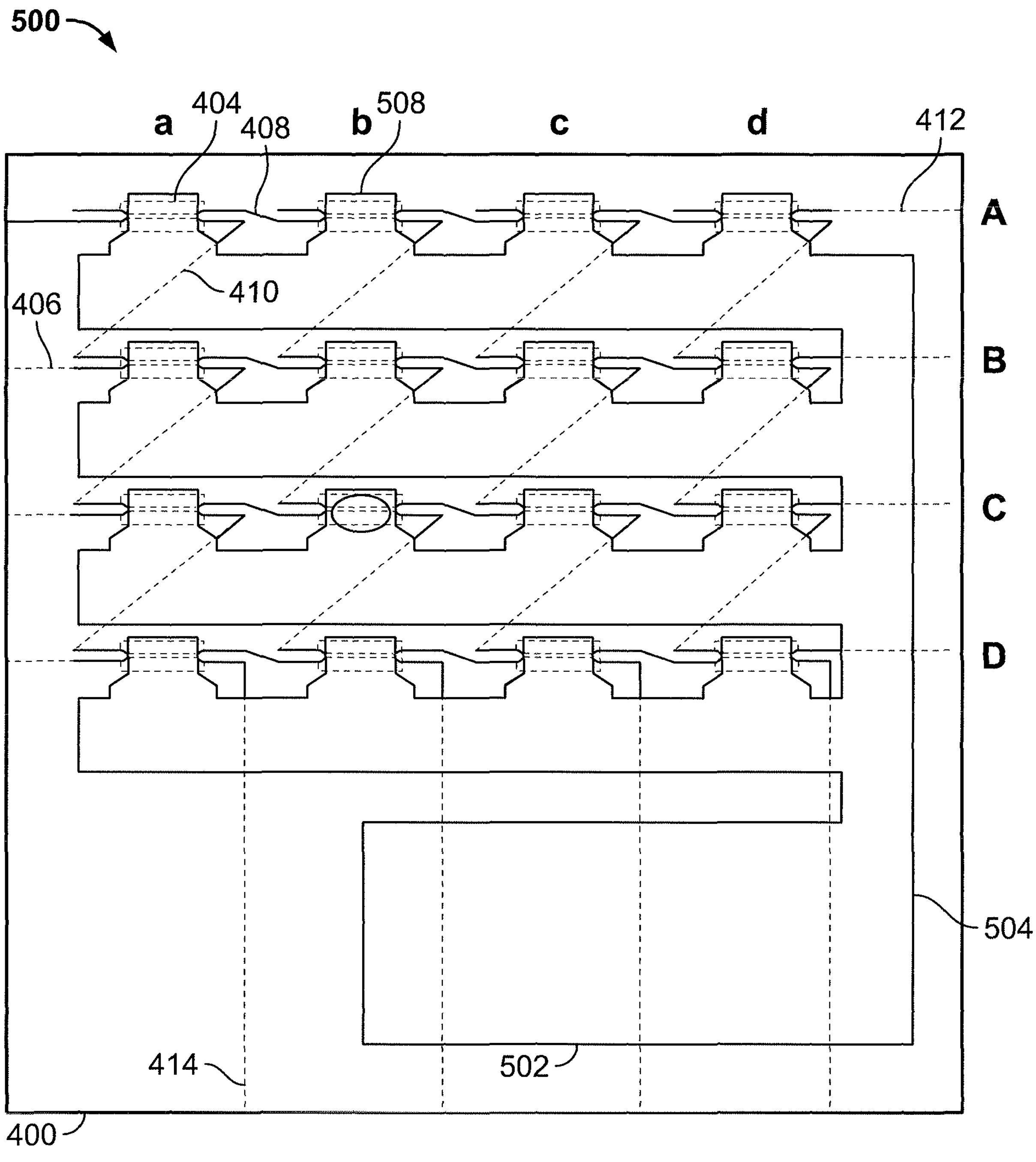

FIG. 6

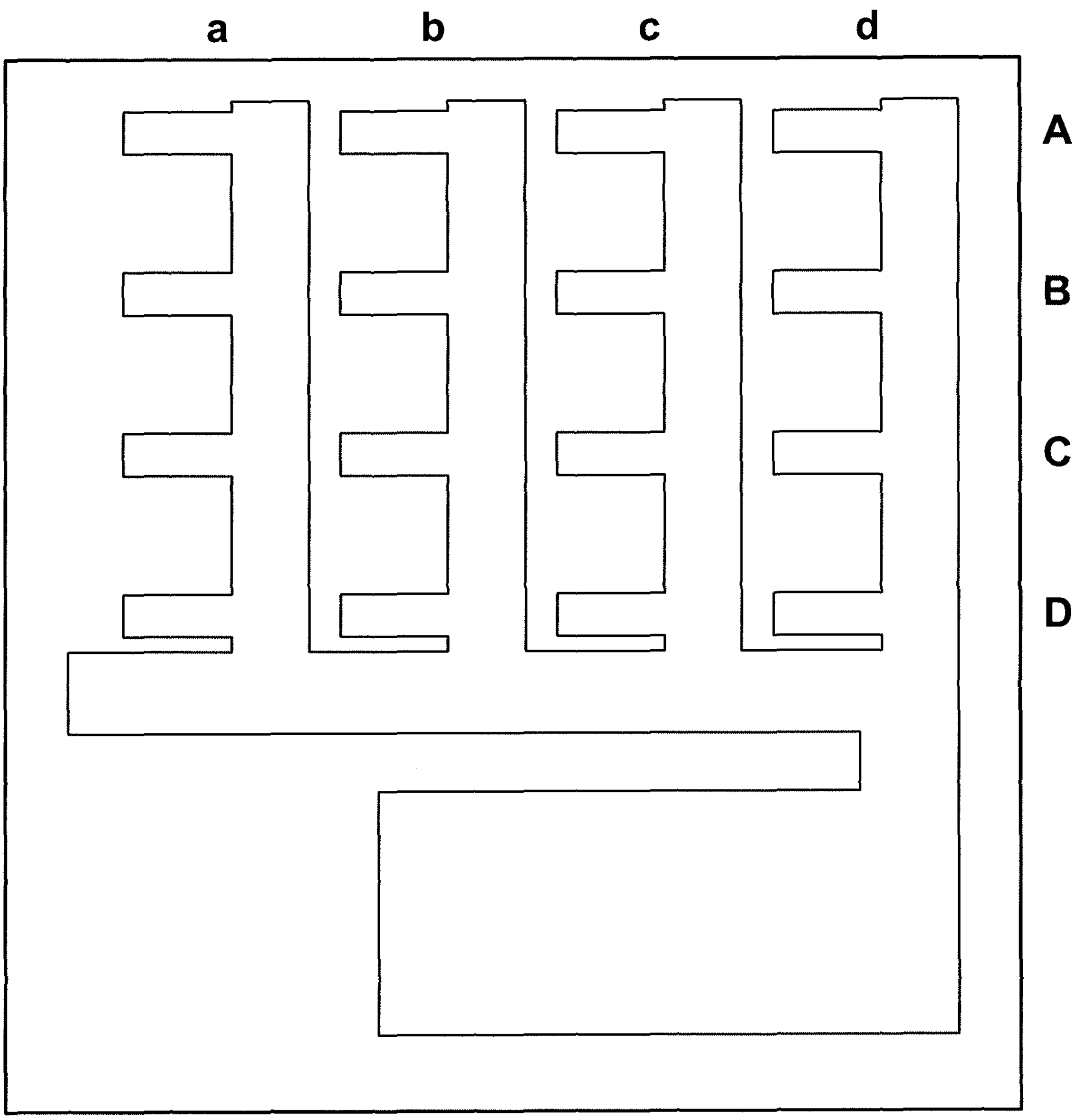

FIG. 7

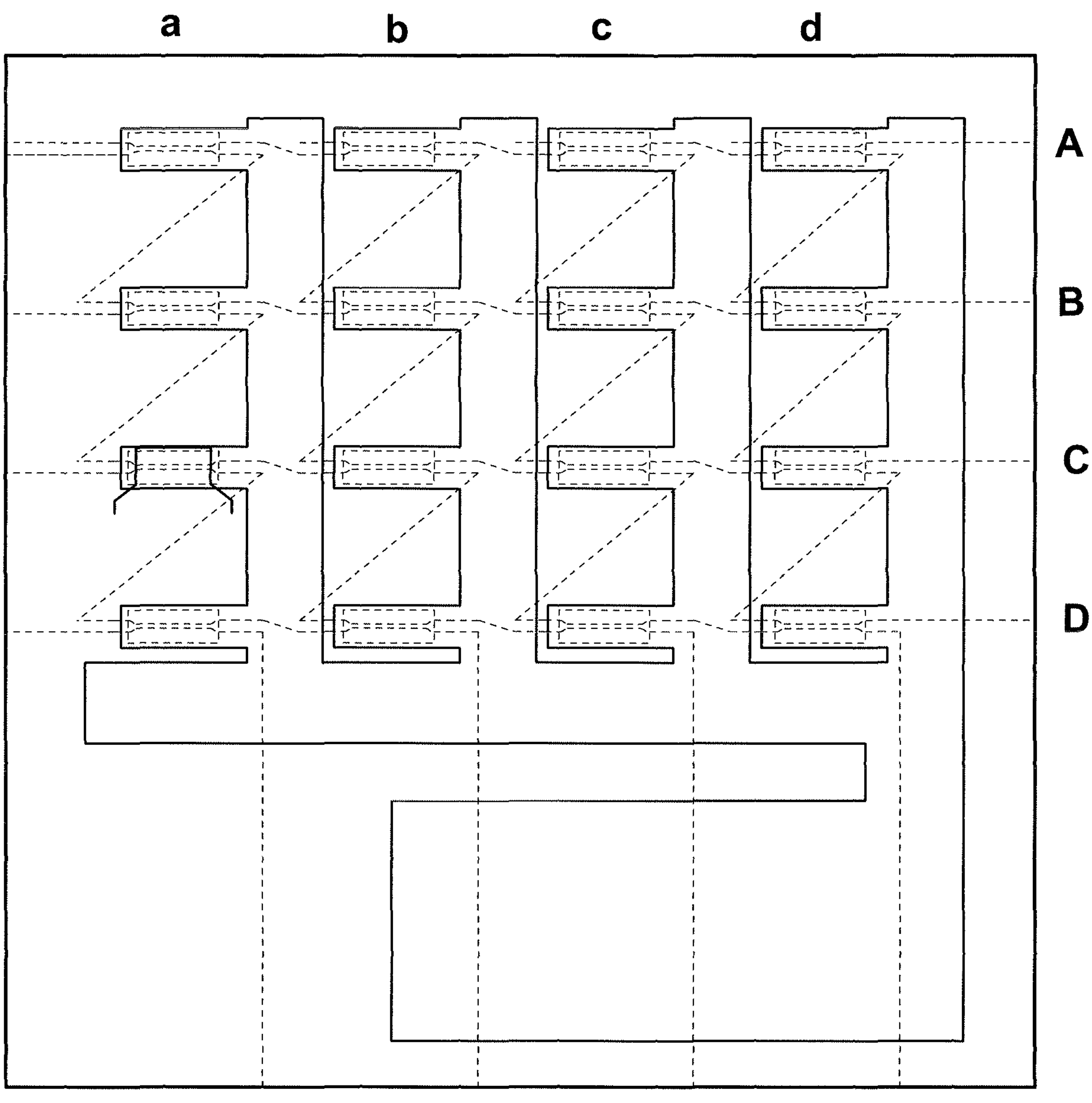

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/060588

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B6/35
ADD. G02B6/12 G02B6/28

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/264844 A1 (BRUEL MICHEL [FR]) 30 December 2004 (2004-12-30) abstract paragraphs [0028] - [0037]; figures 1,2,3 -----	1-34
X	CN 101 799 573 A (UNIV NANJING POSTS & TELECOMM) 11 August 2010 (2010-08-11) abstract paragraphs [0008] - [0019], [0028] - [0031]; figure 1 -----	1-3,6-9, 18-20, 23-26
A	CN 203 101 726 U (UNIV NANJING POSTS & TELECOMM) 31 July 2013 (2013-07-31) abstract paragraphs [0005] - [0021]; figure 1 -----	1-34

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 June 2017	19/07/2017

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Cohen, Adam

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2017/060588

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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CN 203101726 U	31-07-2013	NONE	