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AN OPTICAL SWITCH DEVICE AND METHOD FOR FORMING AN OPTICAL SWITCH DEVICE

Field of the invention

The present invention relates to an optical switch device, and a method for forming such a device. In particular, the present invention relates to an optical switch device for use in optical systems.

Background of the invention

There are a variety of conventional optical switches currently in use, such as electro-optical (EO) switches, acousto-optical (AO) switches, thermo-optical (TO) switches and MEMS mirror switches. Conventional EO switches include EO crystal switches, Mach-Zehnder interferometer switches, and directional coupler switches. EO crystal switches generally have a fast switching speed but they typically require an operating voltage of greater than several tens of volts. An example of an EO crystal switch is described both US Patent 5,044,712 and EP patent application EP 1363158. Conventional AO switches also require high operating voltages. Other conventional EO switches tend to be large in size due to their long coupling length.

Conventional TO switches and MEMS switches are essentially low switching frequency devices, and it is difficult to achieve a high switching frequency such as 50 kHz which is desirable in numerous applications. An example of a TO crystal switch is disclosed in US application 2002/0041726.

In view of the foregoing problems with conventional processes and devices, a need exists for an optical switch and method for producing an optical switch which has a fast switching speed, a low operating voltage and a small size, without reducing production yield or compromising performance.



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Summary of the Invention

In general terms, the invention comprises an optical switch device comprising a waveguide and a liquid crystal cell which is located across the waveguide.

The refractive index of the liquid crystal cell may be changed by an applied electric field which causes a total reflection at the boundary surface between the waveguide and the liquid crystal cell.

The optical switch devices according to an embodiment of the invention aim to have a low operating voltage, a high switching speed and a compact size. Such devices thereby enable systems in which they are used to be smaller in size and have a lower power consumption and a faster switching response than conventional systems.

According to a first aspect of the present invention there is provided an optical switch device comprising:

- a waveguide core having a longitudinally extending axis;

- a cladding layer surrounding said waveguide core;

- a liquid crystal cell mounted in said waveguide core, said liquid crystal cell being positioned across said waveguide core and extending in a plane at a predetermined angle to said longitudinal axis of said waveguide core; and

- a pair of electrodes, one electrode being located above said liquid crystal cell and the other electrode in said pair being located below said liquid crystal cell.

Preferably, said liquid crystal cell comprises a polymer-dispersed liquid crystal, or a polymer-stabilized liquid crystal, in particular a polymer-stabilized ferroelectric liquid crystal.

The liquid crystal cell acts as a switching element.

According to a second aspect of the present invention there is provided a device comprising an array of the optical switch devices defined above.

According to a third aspect of the present invention there is provided a device comprising a tree structure, said tree structure comprising $(2^n - 1)$ optical switch devices of the type defined above, where n is a positive integer, said waveguide cores of each of said optical switch devices having one inlet and two outlets.

According to a fourth aspect of the present invention there is provided a device comprising an array of optical switch devices of the type defined above, said waveguide cores of each of said optical switch devices having M inlets and N outlets, each of said optical switch devices comprising L liquid crystal cells, each of said liquid crystal cells being positioned across said inlets and said outlets of said waveguide cores and extending in a plane at a predetermined angle to said longitudinal axes of said waveguide cores; said device further comprising L pairs of electrodes, one electrode in each of said pairs being located above said liquid crystal cells and the other electrode in said pairs being located below said liquid crystal cells, where L , M and N are positive integers and L is equal to $(M + N)$ or smaller than $(M + N)$.

According to a fifth aspect of the present invention there is provided a method for forming an optical switch device comprising the steps of:

depositing a first cladding layer on a substrate;

forming a waveguide core layer on said cladding layer, said waveguide core having a longitudinally extending axis;

mounting a liquid crystal cell in said waveguide core layer, said liquid crystal cell being positioned across said waveguide core layer and extending in a plane at a predetermined angle to said longitudinal axis of said waveguide core layer; and

forming a pair of electrodes in said cladding layer, one electrode being located above said liquid crystal cell and the other electrode in said pair being located below said liquid crystal cell.

Brief description of the drawings

Preferred features of the invention will now be described, for the sake of illustration only, with reference to the following Figures in which:

Figure 1a is a schematic cross-sectional top view through a crystal switch according to an embodiment of the invention;

Figure 1b is a schematic cross-sectional side view through the crystal switch of Figure 1a;

Figure 2 is a schematic diagram illustrating a fabrication process according to an embodiment of the invention;

Figure 3 is a schematic cross-section through a 1 x 2 optical switch according to an embodiment of the invention;

Figure 4 is a schematic cross-section through a crystal switch according to an embodiment of the present invention and showing the two states of the liquid crystal forming the switch;

Figure 5 is a schematic cross-section through an alternative crystal switch according to an embodiment of the present invention and showing the two states of the liquid crystal forming the switch;

Figure 6 is a schematic diagram showing a combination of 1 x 2 optical switches forming a 1 X 2ⁿ optical switch configuration according to an embodiment of the invention; and

Figure 7 is a schematic diagram of a multi-way switch according to an embodiment of the invention forming an M x N switch configuration.

Detailed Description of Preferred Embodiments

The method and device which illustrate embodiments of the present invention will be explained with reference to Figures 1 to 7. The elements of the optical switch structure illustrated in any one of the Figures which correspond exactly to elements in the structures shown in the other Figures are allotted the same reference numerals.

Figures 1a and 1b show respectively a top view and a side view of an optical switch according to an embodiment of the present invention. The optical switch comprises an optical waveguide core 1 surrounded by cladding or 'clad' 2. A liquid crystal cell 3 is mounted in the core 1 so that it cuts across the core 1 of the waveguide. A pair of electrodes 4 is embedded in the cladding 2, one electrode being placed above the liquid crystal cell 3 and the other electrode being placed below the liquid crystal cell 3. The electrodes 4 and the liquid crystal cell 3 are tilted against the longitudinal direction of the waveguide core 1 at a predetermined angle.

The waveguide core 1 has a lower refractive index than the cladding 2. When a positive electric field E_p is applied between the electrodes 4, the refractive index of the liquid crystal cell 3 is equal to that of waveguide core 1, namely n_0 . Under this condition, the incident light 5 which is parallel to the waveguide

core 1 can be propagated through the liquid crystal cell 3 and to a point "a". A light 6 whose incident angle is larger than zero is also propagated through the liquid crystal cell 3 and to a point "c". This may be regarded as the "on" state of the switch.

When a negative electric field E_n is applied between the electrodes 4, the refractive index of the liquid crystal cell 3 is n_1 , which is smaller than the refractive index n_0 of the waveguide core 1. If n_1 is sufficiently smaller than n_0 , total internal reflection takes place at the boundary surface between the liquid crystal cell 3 and the waveguide core 1. Incident rays 5 along the longitudinal axis of the waveguide core 1 and the incident rays 6 at an angle to this axis are reflected towards the points "b" and "d" at the boundary surface between the waveguide core 1 and the liquid crystal cell 3. This corresponds to the "Off" state of the switch. In this manner, the device works as an optical switch.

The fabrication process of an optical switch according to an embodiment of the invention is shown in Figure 2. In the first stage, a first cladding layer 2 is deposited on a substrate using, for example, a spin-coating technique. The lower electrode is then formed on the first cladding layer 2 by, for example, sputtering and etching the electrode material deposited on the cladding layer 2.

A further layer of cladding material 2 is deposited on the electrode and, if necessary, a planarization treatment is performed on the surface of the further cladding layer 2.

A core layer 1 is formed on the further cladding layer 2 and the core layer 1 is patterned using a photolithographic technique. The core layer 1 is then etched according to the applied pattern. After etching, a further cladding layer 2 (not shown in Figure 2) may be deposited on the etched core layer 1 so as to surround the core layer 1 and, if necessary, a planarization treatment is

performed on the surface of this further cladding layer 2 until the top of the core layer 1 is exposed. A pit for containing the liquid crystal of the core 1 is then etched into the core layer 1. Thus, the waveguide core 1 and the pit for the liquid crystal cell are fabricated on the cladding layer 2.

The pit is then filled with liquid crystal material, such as polymer-dispersed liquid crystal or a polymer-stabilized liquid crystal compound, and a filler, and the material and filler are then polymerized. After the pit is filled with the compound of polymerized liquid crystal material and filler, a further cladding layer is deposited over the surface of the device and the upper electrode is formed thereon. The upper electrode is then covered with additional cladding material thereby completing the fabrication process.

Figure 3 shows an embodiment of the invention in the form of a 1 x 2 optical switch, that is a switch with one inlet I and two outlets O1 and O2. The waveguide for the switch consists of a Y-shaped branch having the one inlet I and the two outlets, O1 and O2. Two liquid crystal cells LC1 and LC2 are located at the junction of the Y-shaped branch so as to cut across the outlets O1 and O2 of the Y-shaped branch. The liquid crystal cells LC1, LC2 act as the switching elements. The incident light from the inlet I is passed to either outlet O1 or O2, depending on the states of the liquid crystal cells LC1, LC2.

Polymer-stabilized Ferroelectric Liquid Crystal (PSFLC) is an example of a suitable material for forming the liquid crystal cells LC1, LC2 in this embodiment as it provides the desired switching speed.

When a positive electric field E_p is applied to one of the liquid crystal cells, for example, LC2 (that is the liquid crystal cell in the branch having the outlet O2), the refractive index of the liquid crystal cell LC2 becomes n_0 , which is equal to the refractive index of the core material of the waveguide. As the refractive indices for the liquid crystal cell LC2 and the waveguide core material are the same, the light propagated in the waveguide can be transmitted through the

liquid crystal cell LC2 without reflection. At the same time, if a negative electric field E_n is applied to the other liquid crystal cell, LC1 (that is the liquid crystal cell in the branch having the outlet O1), the refractive index of the liquid crystal cell LC1 changes to n_1 . If n_1 is sufficiently smaller than n_0 , all of the light from the inlet I propagating towards the outlet O1 is reflected on the boundary surface between the waveguide and the liquid crystal cell LC1. Thus, all of the light from the inlet I proceeds to the liquid crystal cell LC2 and propagates in the outlet O2. This state is regarded as O1 is off and O2 is on.

When a negative electric field E_n is applied to one of the liquid crystal cells, for example, LC2, the refractive index of the liquid crystal cell LC2 changes to n_1 . If n_1 is sufficiently smaller than n_0 , all of the light from the inlet I propagating towards the outlet O2 is reflected on the boundary surface between the waveguide and the liquid crystal cell LC2. If a positive electric field E_p is then applied to the other liquid crystal cell LC1, the light from the inlet I will pass through the liquid crystal cell LC1 and through the outlet O1. The refractive index of the liquid crystal cell LC1 becomes equal to n_0 and light is allowed to pass through the cell. This state is regarded as O1 is on and O2 is off.

Figure 4 shows a schematic view of the crystals in a liquid crystal cell formed of Ferroelectric Liquid Crystal (FLC) and the variation in alignment of the crystals with positive and negative applied voltage. An FLC molecule has an electric polarization. Therefore, the orientation of the molecule changes according to an applied electric field so that the direction of the FLC molecule's electric polarization becomes parallel to that of applied electric field (see Figure 4).

The liquid crystal cell for use in an embodiment of the present invention is not limited to being formed of FLC and an example of another liquid crystal cell suitable for use in an embodiment of the invention is Nematic Liquid Crystal

(NLC) which is shown in Figure 5. The orientation of the NLC molecule changes, for example, between parallel to the electrodes whilst no electric field is applied and perpendicular to the electrodes whilst an electric field is applied, as shown in Figure 5.

Polymer Stabilized Ferroelectric Liquid Crystal (PSFLC) or Polymer Dispersion Liquid Crystal (PDLC) are also suitable for use in an embodiment of the present invention, from the viewpoint of fabrication. After the pit has been filled with the compound consisting of liquid crystal and filler material made of a polymer, a polymerization process follows. An appropriate polymerization process is chosen according to the filler material, for example, exposing the material to a UV light source or heating the material. If necessary, an electric field is applied during the polymerization process in order to align the initial orientation of the liquid crystal molecule. The material disclosed in Japanese Patent applications numbered P1993-247465, P2001-316666, P2000-147476A or Japanese Patent No. 2863794 is applicable to this invention. Other types of liquid crystal material such as Polymerized ferroelectric liquid crystal are also suitable for use in preferred embodiments of the present invention.

Switches of the type described above and illustrated in Figures 1a, 1b and 3, may be combined to form arrays in which the outlets of the switches are connected to the inlets of further 1×2 switches to form, for example, a 1×2^n optical switch, where n is an integer. An example of such a switch is shown in Figure 6.

The arrangement shown in Figure 6 shows multiple Y-shaped waveguides forming a tree structure. By selecting an appropriate set of switches, the incident light can be passed to any desired outlet of the waveguide tree.

In a further preferred embodiment of the present invention, the device can be expanded to include arrays of $M \times N$ optical switches, where M and N are

positive integers and M is the number of inlets and N is the number of outlets. Figure 7 shows an example of 4×2 switch. The 4×2 optical switch consists of a waveguide core having four inlets and two outlets, a cladding layer (not shown) which surrounds the waveguide core, six pieces of liquid crystal cells LC1, LC2, LC3, LC4, LC5 and LC6 which lie so as to cut across the inlets and the outlets of the waveguide core and six pairs of electrodes (not shown) which are located above and below each liquid crystal cell LC1, LC2, LC3, LC4, LC5 and LC6.

The operating voltage of the optical switches embodying the present invention is of the order of 5 V or less and such switches have a switching speed of around 5 microseconds when a Ferroelectric Liquid Crystal (FLC) is used in the liquid crystal cell(s) LC1, LC2, LC3, LC4, LC5 and LC6. As the switches embodying the invention are much simpler in construction compared with conventional optical switches, the size of devices including such switches can be extremely small. Thus the optical switches embodying the invention have a low operating voltage, a high switching speed and a compact size.

The systems and methods according to the present invention may be particularly useful in the production of devices for use, for example, in an optical telephone exchange switch, an optical router or in any other optical equipment such as communication, network or display systems. The devices embodying the invention enable such systems to have a lower power consumption than conventional devices, to be faster in response and smaller in size.

Various modifications to the embodiments of the present invention described above may be made. For example, other materials and method steps can be added or substituted for those above. Thus, although the invention has been described above using particular embodiments, many variations are possible

within the scope of the claims, as will be clear to the skilled reader, without departing from the spirit and scope of the invention.

Claims

1. An optical switch device comprising:
 - a waveguide core having a longitudinally extending axis;
 - a cladding layer surrounding said waveguide core;
 - a liquid crystal cell mounted in said waveguide core, said liquid crystal cell being positioned across said waveguide core and extending in a plane at a predetermined tilted angle to said longitudinal axis of said waveguide core; and
 - a pair of electrodes, one electrode being located above said liquid crystal cell and the other electrode in said pair being located below said liquid crystal cell.
2. An optical switch device according to claim 1, wherein said liquid crystal cell comprises a compound of polymer and liquid crystal.
3. An optical switch device according to claim 1, wherein said liquid crystal cell comprises a compound of polymer and ferroelectric liquid crystal.
4. An optical switch device according to claim 1, wherein said liquid crystal cell comprises polymerized liquid crystal.
5. An optical switch device according to claim 1, wherein said liquid crystal cell comprises polymerized ferroelectric liquid crystal.
6. An optical switch device according to claim 1, wherein said pair of electrodes is embedded in the cladding layer.
7. An optical switch device according to claim 1, wherein said waveguide core has a higher refractive index than said cladding layer.

8. An optical switch device according to claim 1, wherein said waveguide core comprises a Y-shaped branch having one or more inlets and one or more outlets.
9. An optical switch device according to claim 1, comprising two or more liquid crystal cells.
10. An optical switch device according to claim 8, wherein said Y-shaped branch has a junction, said liquid crystal cell being located at said junction of said Y-shaped branch such as to cut across said one or more outlets.
11. An optical switch device according to claim 1, wherein said liquid crystal cell acts as a switching element.
12. An optical switch device according to claim 1, wherein said waveguide core is Y-shaped and comprises one or more inlets and two or more outlets, said device further comprising:
 - a pair of liquid crystal cells positioned across said waveguide core, said waveguide core having a junction, said liquid crystal cells being positioned at said junction; and
 - two or more pairs of electrodes, one electrode in each pair being located above said liquid crystal cells and the other electrode in said pairs being located below said liquid crystal cells.
13. A device comprising an array of optical switch devices according to claim 1.
14. A device comprising a tree structure, said tree structure comprising $(2^n - 1)$ optical switch devices according to claim 1, where n is a positive integer, said waveguide cores of each of said optical switch devices having one inlet and two outlets.

15. A device comprising an array of optical switch devices according to claim 1, said waveguide cores of each of said optical switch devices having M inlets and N outlets, each of said optical switch devices comprising L liquid crystal cells, each of said liquid crystal cells being positioned across said inlets and said outlets of said waveguide cores and extending in a plane at a predetermined angle to said longitudinal axes of said waveguide cores; said device further comprising L pairs of electrodes, one electrode in each of said pairs being located above said liquid crystal cells and the other electrode in said pairs being located below said liquid crystal cells, where L, M and N are positive integers and L is equal to $(M + N)$ or smaller than $(M + N)$.
16. A method for forming an optical switch device comprising the steps of:
- depositing a first cladding layer on a substrate;
 - forming a waveguide core layer on said cladding layer, said waveguide core layer having a longitudinally extending axis;
 - mounting a liquid crystal cell in said waveguide core layer, said liquid crystal cell being positioned across said waveguide core layer and extending in a plane at a predetermined tilted angle to said longitudinal axis of said waveguide core layer; and
 - forming a pair of electrodes in said cladding layer, one electrode being located above said liquid crystal cell and the other electrode in said pair being located below said liquid crystal cell.
17. A method according to claim 16, wherein the step of forming a pair of electrodes comprises:
- forming a first electrode on said first cladding layer;

depositing a second layer of cladding material on said first electrode;

forming said waveguide core layer on said second cladding layer;

patterning said waveguide core layer to apply a pattern on said waveguide core layer;

depositing a third layer of cladding material so as to surround the core layer;

etching a pit for containing said liquid crystal into said waveguide core layer;

filling said pit with liquid crystal material;

depositing a third cladding layer over said device;

forming a second electrode on said third cladding layer; and

covering said second electrode with additional cladding material.

18. A method according to claim 16, wherein the step of depositing said first cladding layer comprises depositing said layer using a spin-coating technique.

19. A method according to claim 16, wherein the step of forming said first electrode on said first cladding layer comprises forming said first electrode using a sputtering technique and etching the electrode material deposited on the first cladding layer.

20. A method according to claim 16, further comprising applying a planarization treatment on the surface of the further cladding layer prior to forming said core.

21. A method according to claim 16, further comprising applying a planarization treatment on the surface of the third cladding layer prior to forming said pit.
22. A method according to claim 17, wherein the step of filling said pit with liquid crystal material comprises filling said pit with polymer-dispersed liquid crystal material.
23. A method according to claim 17, wherein the step of filling said pit with liquid crystal material comprises filling said pit with polymer-stabilized liquid crystal material.
24. A method according to claim 17, wherein the step of filling said pit with liquid crystal material comprises filling said pit with polymer-stabilized ferroelectric liquid crystal material.
25. A method according to claim 17, wherein the step of patterning said waveguide core layer comprises applying said pattern using a photolithographic technique.
26. A method according to claim 16, wherein the step of forming said pair of electrodes comprises embedding said electrodes in said cladding layer.
27. A method according to claim 16, wherein the step of forming said waveguide core layer comprises forming said waveguide core layer of a material having a higher refractive index than said cladding layer.
28. A method according to claim 16, wherein the step of forming said waveguide core layer comprises forming said waveguide core layer of a Y-shaped branch having one or more inlets and one or more outlets.

29. A method according to claim 16, wherein the step of mounting said liquid crystal cell comprises mounting two or more liquid crystal cells across said waveguide core layer.

30. A method according to claim 28, wherein said Y-shaped branch has a junction, and wherein the step of mounting said liquid crystal cell comprises locating said cell at said junction of said Y-shaped branch such as to cut across said one or more outlets.

31. A method according to claim 16, wherein the step of forming said waveguide core layer comprises forming said waveguide core layer of a Y-shaped branch having one or more inlets and two or more outlets.

32. A method according to claim 31, wherein the step of mounting said liquid crystal cell comprises positioning a pair of liquid crystal cells across said waveguide core, said waveguide core having a junction, said liquid crystal cells being positioned at said junction.

33. A method according to claim 32, wherein the step of forming said pair of electrodes comprises forming two or more pairs of electrodes, one electrode in each pair being located above said liquid crystal cells and the other electrode in said pairs being located below said liquid crystal cells.

34. A device comprising an array of optical switch devices formed according to the method of claim 16.

35. A method for forming a device comprising a tree structure, said tree structure comprising $(2^n - 1)$ optical switch devices formed according to the method of claim 16, where n is a positive integer, said waveguide cores of each of said optical switch devices having one inlet and two or more outlets.

36. A method for forming a device comprising an array of optical switch devices formed according to the method of claim 16, comprising forming said

waveguide cores of each of said optical switch devices with M inlets and N outlets, and forming each of said optical switch devices with L liquid crystal cells, positioning each of said liquid crystal cells across said inlets and said outlets of said waveguide cores so that said cells extend in a plane at a predetermined angle to said longitudinal axes of said waveguide cores; forming L pairs of electrodes, one electrode in each of said pairs being located above said liquid crystal cells and the other electrode in said pairs being located below said liquid crystal cells, where L, M and N are positive integers and L is equal to $(M + N)$ or smaller than $(M + N)$.