Broadband 1 × 2 polymer optical fiber switches using nematic liquid crystals

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Abstract

Compact 1 × 2 multimode fiber optic switches are demonstrated using nematic liquid crystals, a polarization beamsplitter and polarizers. Different structures are proposed for showing that even using NLC with low polarization crosstalk, the device working can be improved using alternative configurations. The switch output ports exhibit an optical interchannel crosstalk less than −22 dB, 7 dB fiber to fiber loss and simultaneous operation at 650 and 850 nm with a low power consumption. Applications of the switch include coarse WDM and optical fiber sensor networks.

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1. Introduction

Perfluorinated (PF) polymer based GI-POF (Graded Index Polymer Optical Fibers) has a low loss wavelength region from 500 to 1300 nm [1] allowing implementation of coarse WDM in high-speed, reconfigurable POF networks. For doing so, compact, low loss, high isolation, and low cost optic switches will be required. On the other hand, POF are becoming an attractive medium in sensor networks, specially in flammable atmospheres because optical fibers are intrinsically safe in nature, with no risk of explosion even under malfunction operation, because they are inert materials [2,3]. The optical technology has other advantages such as no EMI, low weight, and as a transmission medium: low loss and wide bandwidth. In those networks, being the security a fundamental matter, it is important to have redundant paths and optical elements for switching between them.

Many kinds of optical switches have been reported. Nowadays, microelectromechanical systems (MEMS) [4,5] are quite attractive due to their large scale integration, fiber-to-fiber coupling, high crosstalk ratios and speed, they used moving parts for switching. Switches based on liquid crystals (LC) cells [6–10] also cover the previous needs with no moving parts, low voltage driving, and low power consumption. However, most of them are based on rather complicated structures [6–8] with a great number of elements. A simpler solution is given in [9] but a fiber optic circulator is needed which complicates its integration. A compact optical switch based on a NLC cell and two calcite Thompson-prism polarizing beam splitters has been previously reported [10]. This switch uses the same conception as we propose in the simplest structure of this paper; but using more expensive components, at a single wavelength, not in combination with optical fibers, neither in a multimode configuration for POF networks.

LC switches are based on nematic [6,8,10,12] or ferroelectric liquid crystals (FLC) [7,11] and the last ones exhibit a faster switching speed of tenths of microseconds. Although the novel structures reported in this paper can operate with both LC cells, the developed prototypes used twisted nematic liquid crystals (NLC) because the devices must operate at 650 and 850 nm, simultaneously. The FLC cells should have different thickness (d) for a proper operation at each wavelength (λ); because the optical birefringence of the FLC material, Δn, depends on λ and to have a 90° polarization switch the product $\Delta n \times d$ must be a constant. In NLC cells, only the Mauguin's regime, $\Delta nd/\lambda \gg 1$, must be fulfilled at both λs.

With these issues in mind, this paper proposes compact, broadband fiber optic 1×2 switches with a reduced number of elements at the expense of a minimum 3 dB insertion losses, and their practical, low cost implementation using NLC cells in combination with plastic optical fibers for being used in a specific application. These NLC require low power levels for working. Different configurations are proposed to improve crosstalk figures. Fiber to fiber losses are in the order or even better than in other previous designs [11,12] and can be improved using better coupling schemes thanks to the high numerical aperture of the POF. These switches can be used in coarse WDM networks [13], POF LANs to allow for redundant paths and sensor time division multiplexing in inflammable atmospheres [2,3]. All of these applications do not need a high speed switching in order to be effectively used.

2. Fiber optic switch structures

The simplest structure of the 1×2 fibre optic switch proposed, named S1, is shown in Fig. 1. Only one polarization is processed for limiting the number of components. In POF multimode fibers, a random polarization will be always present at the input, so the device will operate properly, but at the expense of a minimum of 3dB insertion losses. In this 1×2 fibre optic switch, there are two states: straight state (from 1 to 2) and exchanging state (from 1 to 3) see Fig. 1. For changing states in the switch, a low cost 90° NLC polarization switch (PS) is used. Three sets of lenses are used, for collimating and focusing the light. The other elements are a 90° polarization beam splitter (PBS) and a polariser, P. In our experiment, an s-polariser filters the vertical s-polarised light from the input power, that is 50% of the incident power in a multimode fibre. For the s-polarised beam, when PS is *off* the switch performs the straight state, SS mode. PS rotates the s-polarised beam to a p-polarised beam which passes through the PBS and then is focused to port2. But, when PS is *on* the switch performs the exchanging state, ES mode. PS leaves unaltered the s-polarised beam that is deflected 90° by the PBS towards port3. For monitoring purposes, two 90/10 POF splitters are used at each output. Photographs of the implemented devices can be seen in Fig. 2, where their different elements are marked. A microcontroller drives the NLC depending on the desired state of operation.

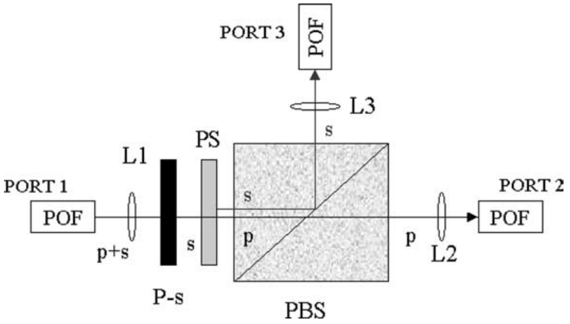

Fig. 1. A schematic of the simplest broadband 1×2 multimode fiber optic switch with a NLC cell, switch S1. POF: polymer optical fibers; PS: NLC polarization switch; PBS: polarization beam splitter; P: polarizer; and L: focusing/collimating lens.

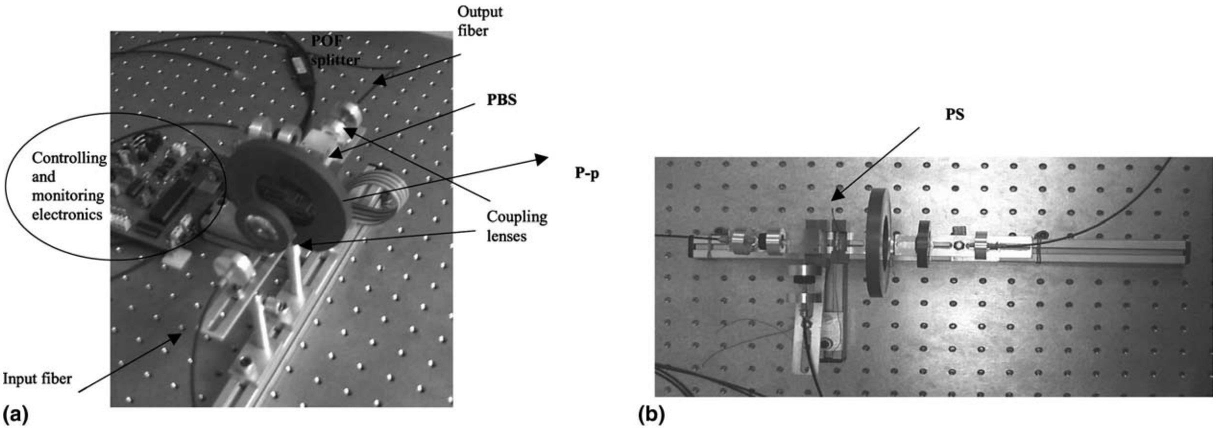

Fig. 2. Photographs of the simplest broadband 1 × 2 multimode fiber optic switch implemented: (a) working in its exchanging state; (b) a top view for showing the NLC cell, PS.

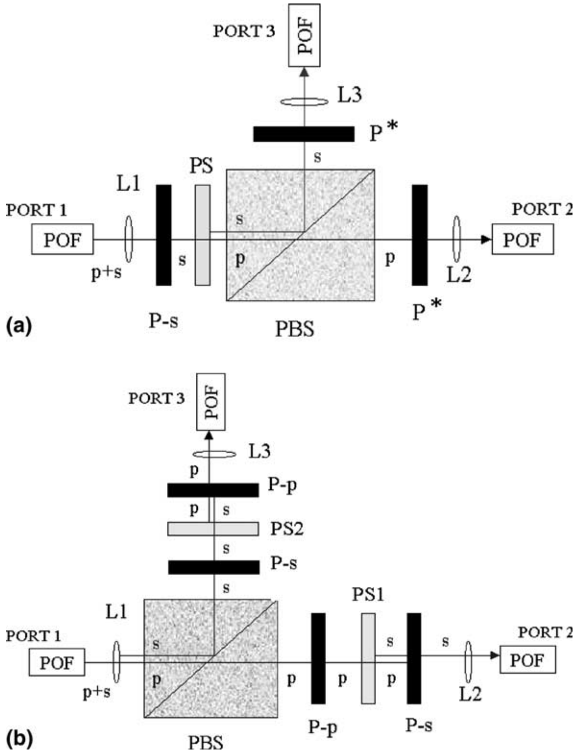

Fig. 3. A schematic of the compact broadband 1 × 2 multimode fiber optic switches with improved crosstalk. (a) Switch S2; (b) switch S3.

Other two novel structures (see Fig. 3) are proposed to improve the S1 switch crosstalk; worsened by the rotations errors in the NLC cell [6]. The schematic of Fig. 3(a), shows S2 switch, where only two new polarisers are included at each output of the PBS for filtering the undesired polarization component (s at port2 and p at port3). This configuration is used to verify crosstalk improvement with the same NLC. But the best results are obtained with the structure shown in Fig. 3(b), S3 switch, where two NLC are included with two polarisers in each LC cells at both outputs. In Table 1 are shown the different switching states.

3. Experimental demonstration of the 1 × 2 fiber optic switches

The 1 × 2 fiber optic switches were experimentally demonstrated using lens for collimating and focusing the light. The insertion loss, and the interchannel crosstalk of the switches were measured using 650 nm semiconductor laser diodes ROITHNER 660/3LJ working at a central wavelength of 660 nm. Switch operation in a 10 MBd link was characterized using the transmitter HFBR-1528 (LED) at the input and the receptors HFBR-2528 at both outputs. The POF splitters are 90/10. The input and output fiber ports are made of POF (HFBR-E889328-C) with 1 mm core, a numerical aperture of 0.447 and 0.25 dB/m losses.

Another feature of the device is that can operate at 650 and at 850 nm. So we have measured the response of the NLC cell at both wavelengths for different excitation signals. The NLC cell is placed

Table 1

Interchannel crosstalk (dB)	S1 (PS)	S2 (PS)	S3 (PS1/PS2)
SS	−8.4 (OFF)	−16.4 (OFF)[a]	−21.3 (OFF/ON)
ES	−13.3 (ON)	−18.4 (ON) [b]	−26.4 (ON/OFF)

Worst case experimental measurements of the interchannel crosstalk for different switching states. SS: Strait state from 1 to 3; ES: exchanging state from 1 to 3; and PS, NLC polarization switch (excitation state).

[a] $P^* = P - p$ (p, Polariser).

[b] $P^* = P - s$ (s, Polariser).

between two broadband PBS, from Melles Griot 03 PBB 013, acting as two cross-polarizers. Depending on whether the LC cell is excited or not, the minimum or maximum transmission is obtained. The LC cell drive signal is a square wave at different frequencies: 100 Hz, 1 kHz, 10 kHz and 100 kHz. A light source from Roithner Lasertechnik is used in the characterization: LDM808/5LJM @808 nm. The NLC cell works properly at both wavelengths reaching the ON/OFF stages at almost the same voltage ranges. So they can be used to implement the broadband switch for working at both wavelengths. Other parameters of the LC cell that have also been measured are: insertion losses of 0.7 dB and a crosstalk of 14 dB @606 nm and insertion losses of 0.9 dB and a crosstalk of 12 dB @808 nm. Relaxation times of 33 ms are measured for both wavelengths.

The interchannel crosstalk is defined as $-10\log(P_{2\mathrm{ON}}/P_{3\mathrm{OFF}})$ and $-10\log(P_{3\mathrm{ON}}/P_{2\mathrm{OFF}})$ in the SS stage and ES stage, respectively. Their measured values for the different configurations and the different switching states are given in Table 1. An interchannel crosstalk improvement of 13 dB from S1 to S3 is obtained. The PBS has a crosstalk of −18.1 dB and the NLC cell of −8.5 dB, both in the worst case. So S3 greatly improves the performance of both devices (see Table 1) having an interchannel crosstalk levels of −21.3 and −26.4 dB. In [6] it is referred a PBS with −40 dB crosstalk, with that device our switch S3 could achieve ∼−44 dB of crosstalk with a simple switch. The improvement in S3 with respect to S1 is due to order alteration, using PBS first instead of the poor NLC cell in terms of crosstalk.

For the switch S1, in the straight state, the fiber to fiber loss is <7.3 dB; while in the exchanging state is <7.2 dB. In any case, the main contribution is the 3 dB intrinsic loss of the polarization sensitive switch and the 2 dB POF coupling loss. This last one can be improved with a better coupling scheme. The NLC cell loss is <0.56 dB. In S3, losses are higher, fiber to fiber loss is <9.6 dB and <9.3 dB in the straight state and exchanged

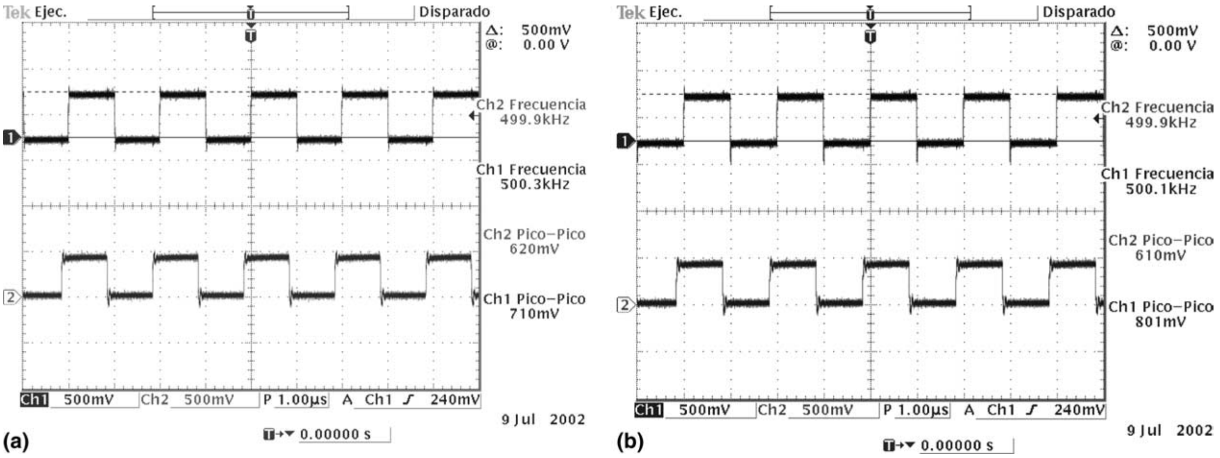

Fig. 4. Measurements on the oscilloscope of the S1 input channel, in a 500 kBd link, and of the S1 switch working output channel: (a) in the SS stage and (b) in the ES stage. CH2 (upper trace): input channel; CH1 (lower trace): output channel.

state, respectively. They are comparable to previous reported results for other switches [11,12] and can be reduced using better BPS and NLC cells and reducing air gaps. Optimum coupling to POF can be reached at a low cost. Measurements are taken using a power meter RIFOCS 557B.

The switch S1 is used in a 500 kBd link, and the measurements are reported in Fig. 4. CH2 is the input power and CH1 is the output power at the SS stage and the ES stage in Figs. 4(a) and (b), respectively. An oscilloscope TDS3052 is used in the measurements. S1 is also used in a 10 MBd link, and the distortion in the input signal due to the transmitter and the receiver limitations does not alter the switch operation (see Fig. 5).

The device operates at a low power consumption, requiring a ± 8 V drive signal for feeding the whole system and almost no current.

The worst measured switching time is of 140 ms, in accordance with the decay times of the nematic LC [6]. This is not a problem in sensor networks where the measurement time is not critical, low cost solutions are required and optical fibers are used because of their non electromagnetic interference and intrinsic safety. As previously reported, a specific example is the oil tank level measurement using optical fibers in the petrol stations [3]. Anyhow this time response can be reduced (e.g., 5 ms) at the expense of increasing complexity and cost by using the high-voltage surface-mode or transient nematic effect [14] as previously reported in a NLC switch in [10].

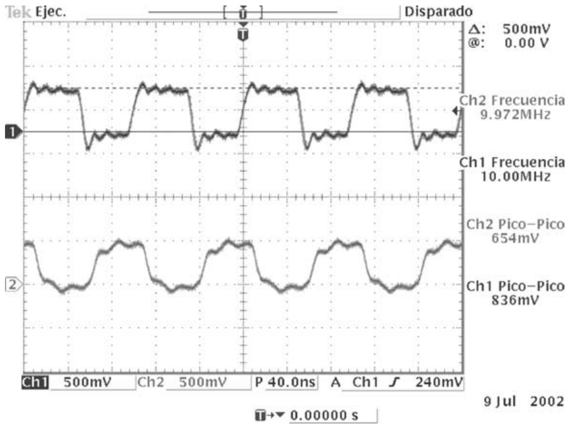

Fig. 5. Measurements on the oscilloscope of the input channel, in a 10 MBd link, and of the S1 switch working output channel in the SS stage. CH2 (upper trace): input channel; CH1 (lower trace): output channel.

4. A specific application

S1 fiber switch has been developed as an autonomous prototype for switching between two redundant paths in a POF network. A dedicated PCB has been developed and the main function of this electronic part is generating and controlling the electrical signal that excites the liquid crystal. Other functions of the electronics are: measuring the optical power of each channel, showing different information on a LCD, visual alarms activation, automatically checking and selection of the working channel.

A fraction of the output power of each channel, from a passive POF splitter, is measured and stored in the microcontroller, a PIC16F877. This information is shown on the LCD along with the state of the different channels, indicating which channel it is working. There is also the possibility to access at a LCD internal menu with the following options:

1. Potencia CANAL1: shows optical power in CHANNEL1 (CH1).
2. Potencia CANAL2: shows optical power in CHANNEL 2 (CH2).
3. Cambiar CANAL: to force a change in output channel.
4. Conmutar CANALES: auto-testing mode, a constant change in the output channel is developed, showing the output power in every position to verify that the device and the network are operative.
5. EXIT: exiting the menu.

A block of three LEDs (input LED, CH1 LED and CH2 LED) is controlled through the PIC, with the following coded message:

- The input LED is green: one of the output channels is working OK.
- The input LED is red (flickering and the other two LEDs are red): none of the two channels is working.
- The CH1 LED is green: CH1 is OK.

- The CH1 LED is red (flickering): CH1 is not properly working.
- The CH2 LED is green: CH2 is OK.
- The CH2 LED is red (flickering): CH2 is not properly working.

A square-wave generator excites the liquid crystal to select the working channel. The PIC16F877 controls that signal, securing that there is always a channel working. If the PIC detects an optical power level below a certain predetermined value (in the present development it is fixed to −12 dBm), it will send an order to activate the liquid crystal and force the working channel to be changed.

4.1. Tests

Different tests have been implemented to verify the correct operation of the device. The most relevant ones are included in the following list:

- It has been forced to change the working channel through the LCD menu.
- A deliberated failure of the main channel (CH1) has been brought about so the device has automatically changed the working channel to CH2, showing a failure message in the LCD.
- Output power at each channel has been measured for different working conditions.
- LEDs light code has been verified.

5. Conclusions

Compact, scalable, broadband, high interchannel crosstalk fiber optic switch configurations are proposed along with their practical, low cost implementation, using NLC cells in combination with plastic optical fibers for being used in a specific application. These NLC require low power levels for working. They are very attractive devices to be used in coarse WDM networks using PF GI-POF and in fiber optic sensor networks. Experimental results on implemented prototypes show crosstalk of −22 dB with poor NLC cells in terms of polarization crosstalk (−8.5 dB). Better available BPS, can improve the crosstalk up to −44 dB. Reduction in the number of elements is achieved at the expense of a minimum 3 dB insertion loss. High numerical aperture POFs reduce cost connections and losses. Fiber to fiber losses can be improved with better couplings to POF, antireflections coatings at the operation wavelength of the polarizers and the NLC cells, and also implementing a polarization insensitive switch by separating both polarizations of the input light with a PBS, processing them and recombining them at the output. The proposed configurations are based in a low cost, planar NLC display technology well established and with a large-scale capability.

Acknowledgements

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