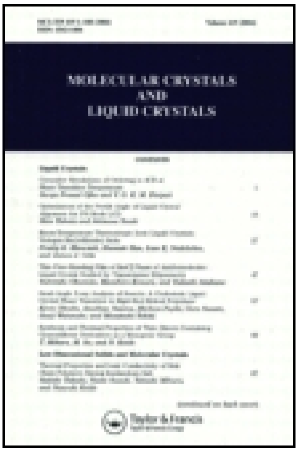

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1 × 2 Optical Router With Control of Output Power Level Using Twisted Nematic Liquid Crystal Cells

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In this work, a reconfigurable 1 × 2 optical router has been designed and experimentally tested. The router allows blocking or redirecting the input light beam to only one of the output ports or to the two output ports simultaneously. A control of the optical power level at each output has also been carried out. As the optical input power fluctuates, the output power is monitored and a feedback control loop adjusts the attenuation and maintains the output power level at a relatively constant level.

Keywords Optical routing; optical power level control; polarization management; protection and recovery applications

1. Introduction

Nowadays, optical routers are key components in optical communications and sensors networks. These devices work by selectively switching optical signals delivered through one or more input ports to one or more output ports, in response to supervisory control signals. Different technologies could be applied to route optical signals, applications of which depend on the topology of the optical network and the switching speed required [1]. The main contemporary routers are made using micro-electromechanical systems (MEMS) [2] and acousto-optical [3], thermo-optical [4], magneto-optical [5] and electro-optical (EO) [6] devices.

EO switches include those based on liquid crystal (LC) devices [7–9]. LC routers use different physical mechanisms to steer the light such as polarization management, reflection, wave-guiding and beam-steering (2D or 3D). Main advantages of this technology include no need of moving parts for switch reconfiguration, low driving voltage and low power consumption. However, these routers cannot respond faster than several microseconds, thus they can be used for telecom and sensor applications in protection and recovery applications, and optical add/drop multiplexing which need fewer restrictions about switching time, like wavelength division multiplexing (WDM) transport network restoration [10].

Usually, twisted nematic (TN) LCs are used in routers based on polarization management. The change of polarization with a TN cell in combination with space polarization selective calcite crystals or polarization beam splitters (PBS) allows optical space-switching.

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Optical transmission is controlled by the voltage applied to the TN cells, lower voltages induce less polarization shifts. Then, these switches can also operate as variable optical attenuators (VOAs) by splitting the input signals at the outputs with a variable ratio depending on the applied voltage and, consequently, on the manipulation of the stage of light polarization by the LC. There have been previous reports on other devices integrating switching and variable attenuation function [11–15].

In this work, a reconfigurable 1 × 2 optical router using TN devices and PBS has been designed and experimentally tested. Input and output ports are made of Plastic Optical Fiber (POF). The router allows blocking or redirecting the input light beam to only one of the output ports or to both output ports simultaneously. A control of the optical power level at each output has also been carried out. This feature can be required, among others, to prevent damages to the optical receivers caused by irregular optical power variations. As the optical input power fluctuates, the output power is monitored and a feedback control loop adjusts the attenuation and maintains the output power level at a relatively constant level.

2. Router Structure

The schematic of the 1 × 2 optical router presented in this work is shown in Fig. 1. In this scheme a light emitting diode (LED) is used as light source. The input and output ports are made of plastic optical fiber, including lenses to collimate the input light and to focus the output light beam. A polarization beam splitter is placed at the input port to divide the non-polarized input beam into two orthogonal components: one component is transmitted with p-polarization and the other is reflected 90° with s-polarization. In each output of the PBS a twisted nematic LC cell, between crossed polarizers, is located to provide the routing function of the input light beam. The system also includes an electronic block to control the router's operation through two independent voltages: V_{LC1}, control voltage of LC cell 1 (LC_1) and V_{LC2}, control voltage of LC cell 2 (LC_2).

Next, a brief description of the router components is presented:

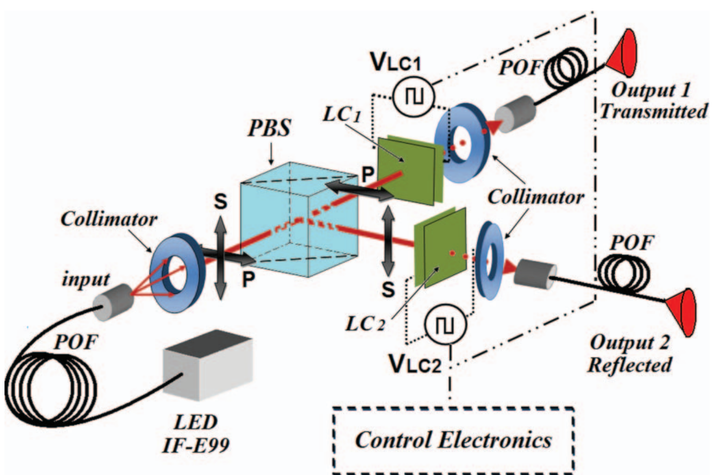

Figure 1. 1 × 2 optical router schematic.

- The LED used is the IF-E99. This high speed LED, housed in a connector less style plastic fiber optic package, has its output spectrum peak at a wavelength of 650 nm with a full width half maximum, *FWHM,* of 10 nm. The device package is optimized with internal microlens to couple into standard 1 mm core POF.
- At the input and output ports, the plastic optical fiber is the POF HFBR-E889 328-C, this fiber has a 1 mm core, its numerical aperture is 0.447 and its losses are about 0.25 dB/m at 650 nm. The input lens is biconvex with a diameter, $\Phi = 25.5$ mm and focal length, $f = 25$ mm, while the lenses at the output ports are plano-convex with $\Phi = 25.5$ mm and $f = 20$ mm. Both outputs are positioned at the same distance from the light source.
- The PBS used in the assembly is of the BPS0402 series, with dimensions of $20 \times 20 \times 20$ mm, it operates at a wavelength range from 650 nm to 850 nm. It presents a transmittance of the p-polarized component, T_P, higher than 95%, and a reflectance of the s-polarized component, R_S, higher than 95%. The split ratio, T_P/R_S, is 50/50 $\pm 5\%$ for random polarized light.
- The TN-LC device operation, between crossed polarizers, is described in Fig. 2. When the applied voltage to the TN-LC device is less than threshold voltage, V_{TH}, the device rotates the linear polarized light, which passes through the polarizer, 90° (waveguide property). This waveguide regime takes place when the phase delay satisfies the condition of the equation (1).

$$\frac{\Delta n d}{\lambda} \gg 1 \tag{1}$$

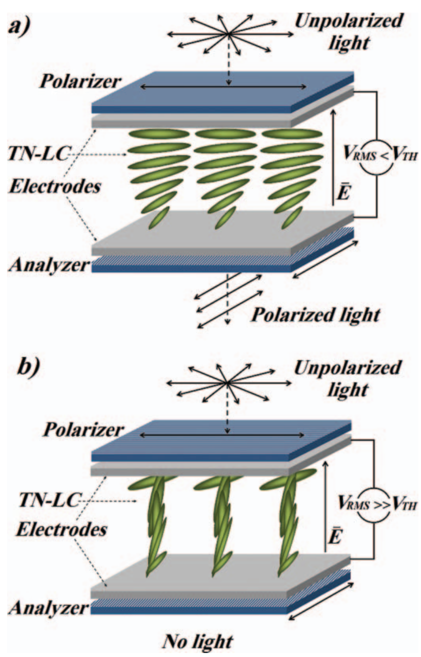

Figure 2. TN-LC device operation: a) under threshold, b) too above threshold.

Where Δn is the optical birefringence of the LC material, d is the thickness of the LC layer, and λ is the wavelength of the light. When this condition is achieved, a maximum optical transmission is obtained (normally white operation mode).
On the other hand, if the voltage applied is much higher than threshold, the molecules are aligned in the direction of the resulting electrical field, and the input light polarization is not rotated, therefore it is blocked by the analyzer (minimum optical transmission). TN devices used in this work have the crossed polarizers integrated into the structure. The LC devices are oriented so that incident polarized light component has the maximum optical transmission through the input polarizer.

- The control electronics provides the V_{LC1} and V_{LC2} signals which define the router operation mode. These signals are 1kHz square waveforms with root mean square (V_{RMS}) values between 0 and 4V. The control signals are generated by a digital-analog converter DAC0800 working in a basic bipolar output configuration. The voltage values and the 1kHz frequency generated by the DAC are achieved by controlling the input binary data using a Spartan3 FPGA (field programmable array).

3. Router Operation and Performance

The incoming light has a random polarization which is split in two orthogonal components with p and s polarization state. Each component goes to a TN-LC cell with the entrance polarizer oriented in the same direction that the incident light. System operation is based on controlling the optical power in output 1 and output 2 through the independent variation of the control signals, V_{LC1} and V_{LC2}, applied to each LC cell. Control electronics, which provides the control signals, allows four basic routing modes, with intermediate values between maximum and minimum transmission, as shown in Fig. 3.

Optical power is being measured by using an optical power meter RIFOCS 557B. In order to get a LED characterization, the optical power is measured at the LED's output. This optical power is also measured on the output 1, without the light passing through the router (only by collimators and air) to know the free-space and fiber-to-fiber coupling losses, L_{CP}. These results are presented on Fig. 4 and show that L_{CP} is about 9.3 dB.

To analyze the optical switch performance, next nomenclature is used:

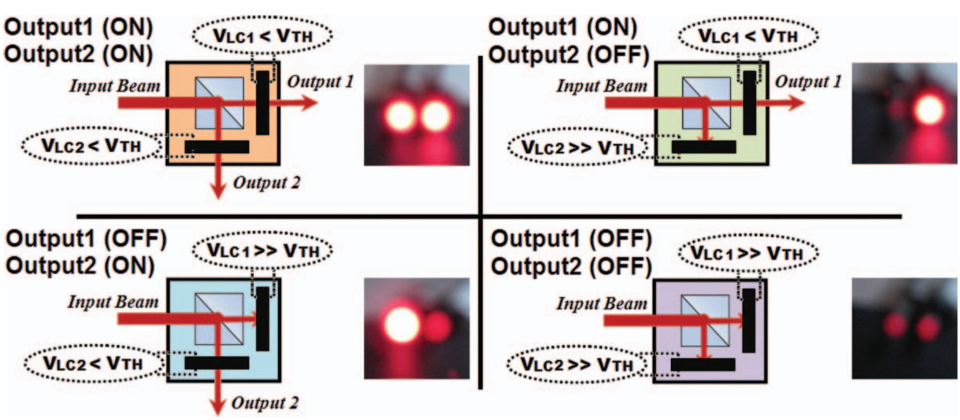

Figure 3. 1 × 2 optical router working modes.

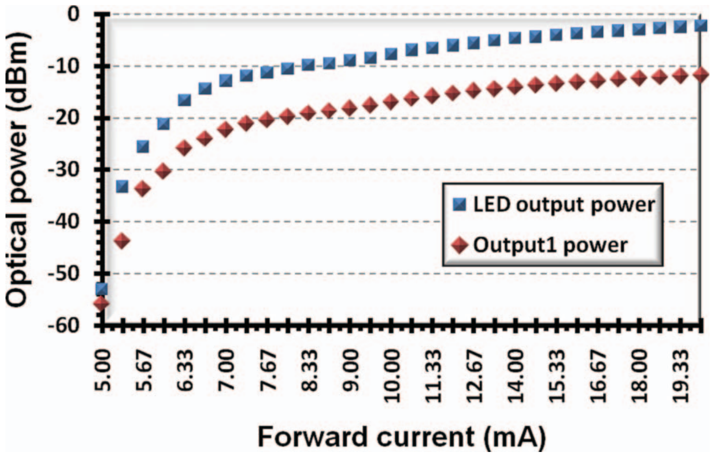

Figure 4. LED optical power as a function of forward current. Measurements at the LED output and at the output 1 without passing the light through the router.

- $P_{OUT(ON)}$: output power of an output port in the ON state (maximum optical transmission), $V_{LC} < 1.5\text{V}_{\text{RMS}}$.
- $P_{OUT(OFF)}$: output power of an output port in the OFF state (minimum optical transmission), $V_{LC} = 4\text{V}_{\text{RMS}}$.
- P_{IN}: incident input power (LED IF-E99 beam), without passing through the optical router (only by collimators and air).

A brief resume of the system parameters measured is show in Table 1, where IL are the optical losses in decibels of PBS (L_{PBS}) and LC (L_{LC}), $IL = L_{PBS} + L_{LC}$. The measured L_{PBS} is 3.65 dB and 3.27 dB for the transmitted and reflected component, respectively. For non polarized light, $L_{LC} = 5.91$dB. On the other hand, for polarized light L_{LC} depends essentially of the quality of LC polarizers, and the orientation of the entrance polarizer with respect to the incident beam. Therefore, the router's IL value can be reduced by improving the alignment of the input polarizer of the LC device and the beam transmitted or reflected by PBS and using polarizers with antireflection coatings at the operating wavelength.

Figure 5 shows the insertion loss of output 1 and output 2 as a function of voltage applied to the LC devices. These experimental results show the symmetry of the two output ports. Finally, the switching time has also been measured, as the time elapsed from

Table 1. Main parameters of the optical router.

Parameter	Definition	Measured Value	
		Output 1	Output 2
Insertion Loss (IL)	$IL = -10\ \log(\frac{P_{OUT(ON)}}{P_{IN}})$	6.39 dB	6.40 dB
Rejection Ratio (RR)	$RR = -10\ \log(\frac{P_{OUT(ON)}}{P_{OUT(OFF)}})$	26.41 dB	25.13 dB
Crosstalk (CR)	$CR = 10\ \log(\frac{P_{OUT(OFF)}}{P_{IN}})$	−32.80 dB	−31.53 dB

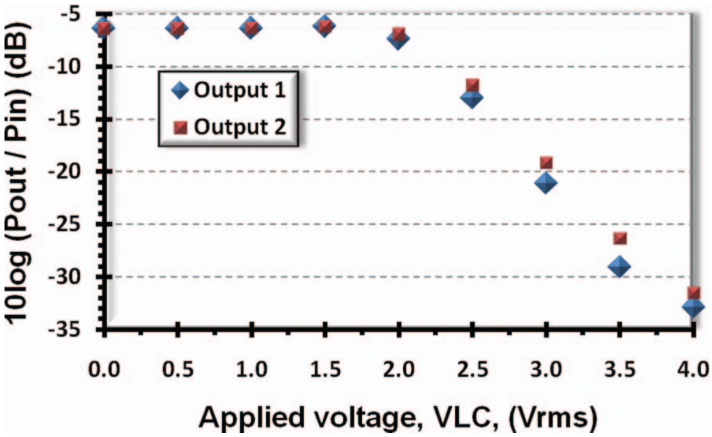

Figure 5. Insertion losses for the outputs 1 and 2 versus the applied voltage to LC cell.

activating the switching command to the moment the *IL* of the switch path achieves the 90% of its final value. The average value has been 15 ms.

4. Output Power Level Control

The optical output power is a direct function of the optical input power, as it can be seen in Fig. 6, for both ports.

This router configuration allows stabilizing the optical output power by using a scheme like the implemented in this work, see Fig. 7.

At each router output, a 90/10 splitter is used to display the output power. A 10% of the optical signal is directed to an IF-E99 phototransistor connected to a transimpedance amplifier with two TL081 operational amplifiers to perform optical to electrical conversion. The resulting voltage level is converted to binary information by an analog-digital converter ADC0804 and sent to a Spartan3 FPGA, which controls the system. The FPGA generates an

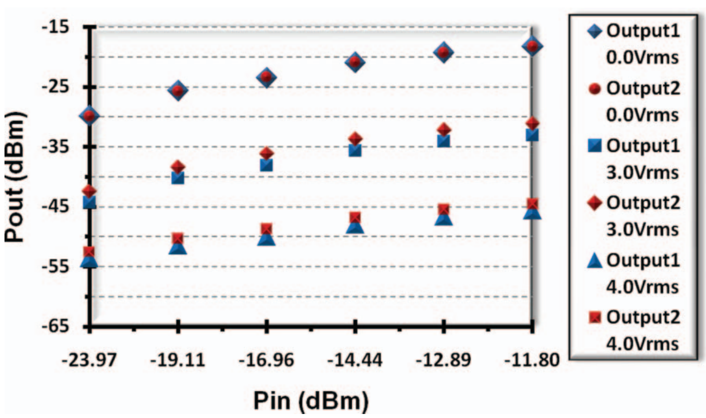

Figure 6. Output power as a function of the input power, for the outputs 1 and 2 with different applied voltages to the LC cells.

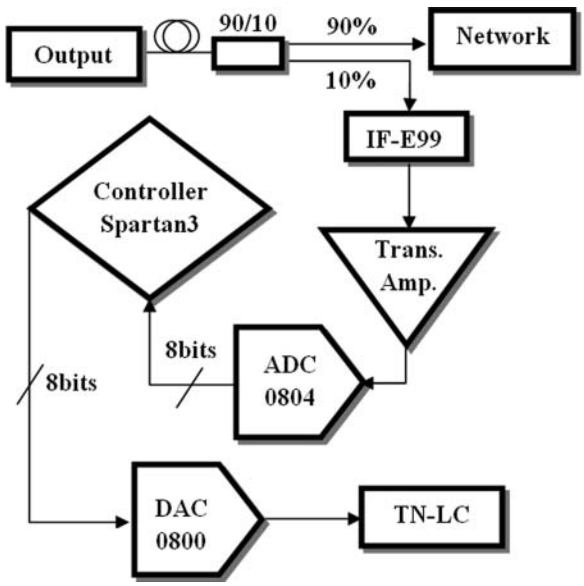

Figure 7. Schematic diagram of the stabilized system.

output signal, S_{LC}, of 8 bits that switches its value between S_{LC} and not(S_{LC}) at a frequency of 1kHz with an encoding that allows the DAC0800, operating at bipolar mode, generating the appropriate control signal to stabilize the output power switch.

Figure 8 shows the optical power stabilization on the output 1, in the face of variations on the optical input power. Additionally, it also shows the direct variation of the optical power on the output 2, without stabilization, as result of the same input variations. The output power can be stabilized to a value, P_{ES}, in a range that depends on the following

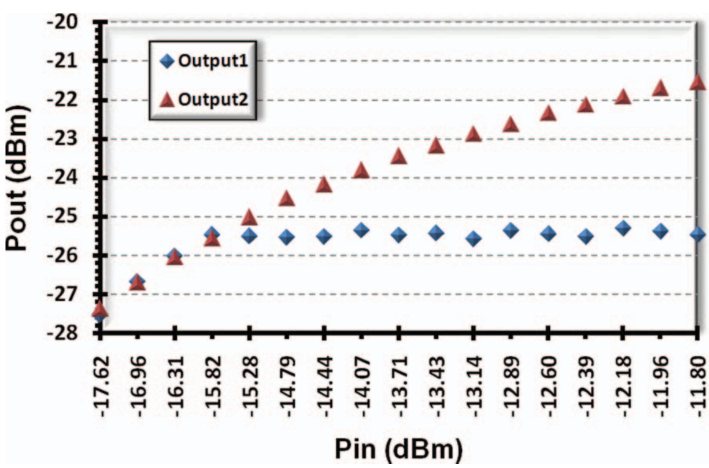

Figure 8. Output power as a function of the input power for the outputs 1 and 2, with the output1 stabilized to −25.7 dBm and without stabilization at the output 2.

parameters: minimum input power of the system, P_{MIN}, maximum power, P_{MAX}, rejection ratio, *RR*, and insertion loss, *IL*, so that $P_{MAX}–IL–RR < P_{ES} < P_{MIN}–IL$.

5. Conclusions

A reconfigurable 1 × 2 optical router has been designed and experimentally tested. The router allows blocking or redirecting the input light beam either to only one of the output ports or to both output ports simultaneously. The router has about 6.4dB insertion loss, 26dB rejection ratio, −32dB crosstalk and 15ms switching time.

Additionally, a control of the optical power level at each output has also been carried out to prevent damages to the optical receivers caused by irregular input power variations. As the optical input power fluctuates, the output power is monitored and a feedback control loop adjusts the attenuation and maintains the output power level at a relatively constant level. This router may be used in applications like POF local area networks for allowing redundant paths or reconfigurable multicasting in access networks.

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