# BROADBAND 1×2 LIQUID CRYSTAL OPTICAL SWITCH WITH LOW THERMAL DEPENDENCE

P.J. Pinzón, I. Pérez, C. Vázquez, J.M.S. Pena

Grupo de Displays y Aplicaciones Fotónicas, Universidad Carlos III de Madrid, Butarque 15, 28911 Leganés, Spain.
Corresponding author: ppinzon@ing.uc3m.es

**Abstract:** In this work, the optimized design of a broadband 1×2 liquid crystal (LC) optical switch (OS) is presented. The design is based on a polarization rotator (PR), which is composed of two nematic LC cells. The azimuth angle and thickness of each LC cell is obtained with a simple computational optimization approach, with performance comparable with more complex existing procedures. The LC-OS is capable to route, in a uniform way, optical signals in the visible spectral range (400 nm – 700 nm) with low thermal dependence in the range from 15ºC to 40ºC, making it ideal for wavelength division multiplexing applications in POF systems.

**Key words:** Optical switch, polarization rotator, liquid crystal devices, computational optimization.

## 1. Introduction

In the last years, wavelength division multiplexing (WDM) has been proposed as one potential solution to expand the usable bandwidth of step index polymer optical fibers (SI-POFs) based systems. This requires the development of devices capable of routing optical signals in a broadband range, in the visible spectrum (VIS), in order to cover proposed SI-POF WDM spectral grid (400 nm − 700 nm) [1].

Optical switches are key components in WDM networks. They selectively switch optical signals delivered through one or more input ports to one or more output ports. Different technologies could be applied to route optical signals [2], [3]. The final choice depends mainly on the optical network topology, switching speed and spectral range required.

Liquid crystal optical switches (LC-OS) are mainly based on polarization modulation in combination with polarization selective calcite crystals to steer the light [4]-[6]. Main advantages of LC technology include no need of moving parts for switch reconfiguration, low driving voltage and low power consumption. Its response time is in the order of milliseconds, so it is ideal for protection and recovery applications and optical add/drop multiplexing, which demand fewer restrictions on switching time [2]. Usually, LC-OS use twisted nematic (TN) LC cells, acting as polarization rotators (PRs) [7]. However, their crosstalk (CT) is optimum only for specific wavelengths, called Mauguin Minima [2], [4]. Besides, LC birefringence, which defines Mauguin Minima, is very temperature dependent [8], requiring temperature compensated designs or controllers.

In this work, the design of a broadband 1×2 LC-OS is presented. It is based in a PR, which consist in a TN LC cell in series with a nematic homogeneous (NH) LC cell. The design has optimum response across 400 nm − 700 nm spectrum with low temperature dependence, up to 40°C. The LC cells are designed with the same thickness and azimuth angle. Therefore, they are easy to join together, which facilitates the LC-OS construction and reduces its losses. The switch performance is simulated with a 3-channels system in the VIS range and it is compared against a non-optimized design (a 1×2 LC-OS based in a single TN cell).

The paper is organized as follows. In section 2, the operation principle and modeling of a LC-PR device is defined. Then, the operation of a LC-OS, based in a PR with a single TN cell, is depicted in section 3. In this section, the wavelength and thermal dependence of the non-optimized LC-OS are analyzed. An achromatic PR is required in order to obtain a broadband LC-OS. Therefore, in section 4, the design of a 2 stages achromatic PR is presented. And, in section 5, the operation of the proposed LC-OS, which is based in the 2 stages achromatic PR, is analyzed in the temperature range from 15ºC to 40ºC. Finally conclusions are given in section 6.

## 2. LC Polarization Rotators

PRs modify the orientation of a linear polarized beam in a specific angle, e.g. from being $x$-polarized (parallel to $x$-axis) to be $y$-polarized (parallel to $y$-axis), which represents a 90º rotation. Most common PR scheme consists of a single TN cell, see Fig. 1, while achromatic or broadband designs include TN cells, retardation plates and/or nematic homogenous LC cells (NHs), see Fig. 6.

### *2.1. Nematic LC devices modeling*

The operation of a LC cell is based on the optical birefringence, $\Delta n$, between the fast and slow axes of its molecules (slow axis is called $c$-axis). A NH cell, with thickness $d$, produces a phase delay between the polarization components of a light beam, with wavelength $\lambda$, that is given by:

$$\Gamma = 2\pi \frac{\Delta n d}{\lambda} \tag{1}$$

The LC $c$-axis angle respect to the cell surface is defined as tilt angle, $\theta$, see Fig. 1c. Without applied voltage, $V$, NHs and TNs cells have $\theta \cong 0^{\circ}$. In a NH cell, the front and rear molecules have the same orientation angle, while in a TN cell there is a twist angle, $\phi$, between them [9]. Therefore, NH cells are a particular case of TN cells with $\phi = 0°$, and their Jones matrix representation [9] is given by:

$$W_H(\alpha) = R^{-1}(\alpha) \times \begin{pmatrix} e^{-i\frac{\Gamma}{2}} & 0 \\ 0 & e^{i\frac{\Gamma}{2}} \end{pmatrix} \times R(\alpha) \tag{2}$$

where $R(\alpha)$ is the rotation matrix of the LC $c$-axis orientation angle, $\alpha$, respect to the $x$-axis, see Fig. 1c; which is given by:

$$R(\alpha) = \begin{pmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{pmatrix} \tag{3}$$

TN cells can be modeled as a stack of $N$ NH layers, with constant $c$-axis orientation angles, varying a total twist angle $\phi$, in increments of $\Delta\phi = \phi/N$. Then, the characteristic matrix of a TN cell [9], with its front $c$-axis oriented at an angle $\alpha$ and total twist $\phi$, is given by:

$$W_T(\alpha) = R^{-1}(\alpha) \times \begin{pmatrix} \cos(\phi) & -\sin(\phi) \\ \sin(\phi) & \cos(\phi) \end{pmatrix} \begin{pmatrix} \cos(X) - i\frac{\Gamma}{2}\frac{\sin(X)}{X} & \phi\frac{\sin(X)}{X} \\ -\phi\frac{\sin(X)}{X} & \cos(X) + i\frac{\Gamma}{2}\frac{\sin(X)}{X} \end{pmatrix} \times R(\alpha) \tag{4}$$

where $X = [\phi^2 + (\Gamma/2)^2]^{1/2}$. It is important to note that the elements [1,1] and [2,1] of $W_H$ and $W_T$ represent the output $x$-polarized and $y$-polarized components, respectively, when the input is $x$-polarized.

### *2.2. TN cell based polarization rotator*

A TN based PR consists of a TN cell bounded between linear polarizers, LPs, parallels to the LC front and rear $c$-axes. Most common design uses TN cells with 90º twist, e.g. input and output LP are parallel to the $x$-axis and $y$-axis, respectively (crossed LPs). In this configuration with $V = 0$ (Fig. 1.a.), from (4), an input $x$-polarized beam is transmitted with $y$-polarization direction, according to:

$$Ty = \left| \cos(\mathrm{B}) - i\frac{\Gamma}{2}\frac{\sin(\mathrm{B})}{\mathrm{B}} \right|^2 \quad \textit{with} \quad \mathrm{B} = [(\pi/2)^2 + (\Gamma/2)^2]^{1/2} \tag{5}$$

On the other hand, when $V$ is higher than a threshold value, $V_{th}$, the LC molecules are tilted in the resulting electrical field direction ($\vec{E}$), $0^{\circ} < \theta < 90^{\circ}$, and they are parallel to $\vec{E}$ when $V \gg V_{th}$, then $\theta \sim 90^{\circ}$ and $\Gamma \sim 0$, there is not a polarization rotation and the light is blocked, as it is shown in Fig. 1.b.

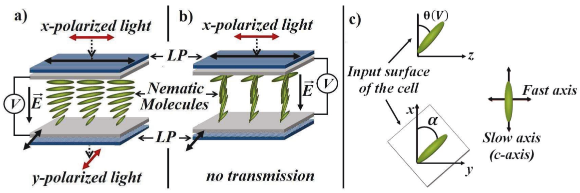


*Fig. 1: TN cell based polarization rotator: a) V<Vth, b) V≫Vth and c) tilt angle, θ, and c-axis orientation angle, α, definition.*

## 3. Liquid Crystal Optical Switch based on a single TN cell

The simplest scheme of a 1×2 LC-OS is based in a polarization modulator in combination with a polarization selective crystal to steer the light, as is shown in Fig. 2. Typically, the polarization modulator consists in a TN cell acting as a PR and the polarization selective crystal is a polarization beam splitter (PBS). A PBS transmits the light beams polarized in the transmission axis direction, e.g. $x$-polarized beams, and reflects the light beams polarized in the reflection axis direction, e.g. $y$-polarized beams.

Following, the operation of the 1×2 LC-OS of Fig. 2 is described. It is based in the simple TN polarization rotator that is described in the previous section and a PBS. When a light beam insides on the input LP, it transmits the $x$-polarized component to the PR. Then, if $V < V_{th}$, the polarization component is rotated to be $y$-polarized and the beam is reflected to the $S_2$ output by the PBS, with a transmission given by Eq. (5). On the other hand, if $V >> V_{th}$, the polarization component is not rotated and the beam is transmitted to the $S_1$ output, with a transmission given by $Tx = 1 - Ty$ (see, Eq. 5).

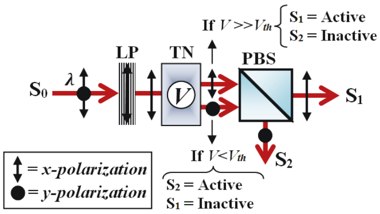


*Fig. 2: Scheme of a 1×2 LC-OS based in a single TN cell.*

In this paper, the LC-OS performance is analyzed in terms of insertion loss, *IL*, and crosstalk, *CT*, paying special attention to their spectral uniformity and thermal stability. The *IL* is defined as the relation between the input power, at $S_0$ port, $P_{S0}$, and the power at the active port, $S_1$ or $S_2$ ($P_{S1}$ or $P_{S2}$, respectively), and it is given by:

$$IL_{\{S1,S2\}} = 10\log_{10}\left( P_{S0} / P_{\{S1,S2\}} \right) \tag{6}$$

this value is > 0dB and should be as small as possible. The *IL* of Fig. 2 scheme is limited to be greater than 3dB, when the input beam is non-polarized, because the LP blocks at least 50% of the input power. This can be overcome by using a polarization diversity scheme. In this paper, polarized input beams are considered, so the minimum IL value is 0dB.

The *CT* is defined as the ratio of the optical power leaked to the inactive output, $S_1$ or $S_2$, from the input power, and it is given by:

$$CT_{\{S1,S2\}} = 10\log_{10}\left( P_{\{S1,S2\}} / P_{S0} \right) \tag{7}$$

the CT is < 0dB, and should be as small as possible.

The *IL* of $S_1$ (when $S_1$ is the active port) and the *CT* of $S_2$ (when $S_2$ is the inactive port) are mainly defined by the LC cells characteristics (e.g. their transmittance and minimum birefringence when $V>>V_{th}$) and the applied voltage. On the other hand, the *IL* of $S_2$, represented as $IL_{S2}$, and the *CT* of $S_1$, represented as $CT_{S1}$, are mainly defined by the polarization rotation efficiency, which depends on the PR design. Therefore, in order to determine the improvement of the proposed design, onwards, only $IL_{S2}$ and $CT_{S1}$ will be analyzed (only when $V<V_{th}$), and for simplicity, we will refer to them as *IL* and *CT*, respectively.

### *3.1. Wavelength dependence*

*Ty* from Eq. (5) is not an achromatic function, it presents periodic peaks at:

$$\frac{\Delta nd}{\lambda} = \frac{1}{2}\sqrt{4N^2 - 1} \quad with \quad N = 1, 2, ... \tag{8}$$

which are also called Mauguin minima [9]. Then, the transmitted beam polarization, at the TN cell output of Fig. 1, is slightly elliptical. Ellipticity ($e$) is defined as the ratio of the $x$-polarization to the $y$-polarization component (a linear polarized beam has $e = 0$).

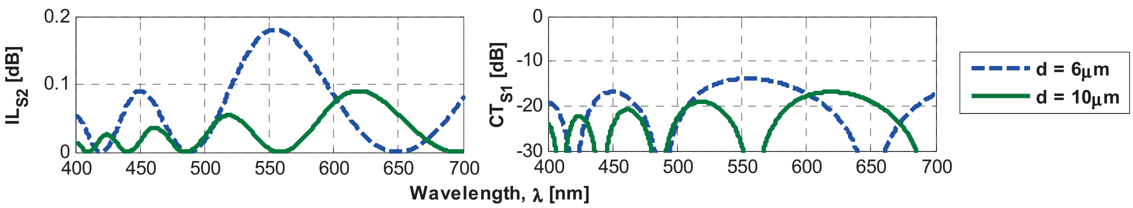


*Fig. 3: Spectral response of a LC-OS based on a TN cell of E7 material with d = 6 μm and d = 10 μm.*

$IL$ can be expressed as $-10\log_{10}(Ty)$ and $CT$ can be expressed as $10\log_{10}(Tx)$, where $Tx = 1 - Ty$. Fig. 3 shows the $IL$ and $CT$, in the VIS range, of two 1×2 LC optical switch, based on 6 µm and 10 µm width TN cells of E7 material. The 6 µm TN cell based PR produce $IL < 0.18$ dB and $CT < -13.9$ dB. Those values can be improved to $IL < 0.10$ dB and $CT < -16.9$ dB by using a 10 µm TN cell, but the response time, $\tau$, is increased by 177%, since $\tau \propto d^2$ [10]. Typically, a 5 µm TN cell has $\tau \sim 20 - 30$ ms [11].

### *3.2. Temperature dependence*

An important issue of LC-OSs based in a single TN cell is their temperature dependence. As is shown in Fig. 3, TN cells present periodic minima, given by Eq. (8). Those minima are defined by the LC birefringence, which is very temperature dependent. In [8], the Cauchy model, which defines the LC birefringence of the E7 material for different temperatures, is presented. This information is used to plot the E7 birefringence in the range from 15º to 40º in the Fig. 4, and for the next temperature simulations.

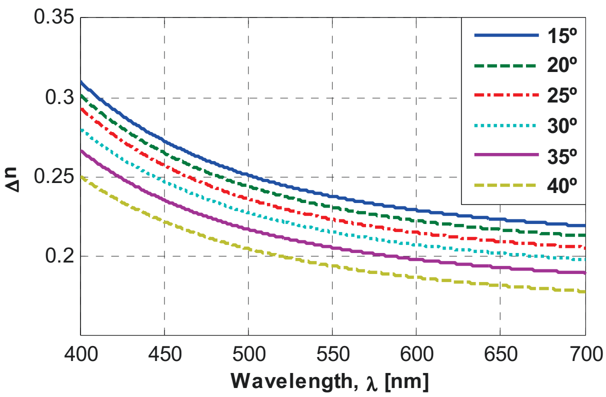


*Fig. 4: Birefringence variation of the E7 LC material in function of temperature in ºC.*

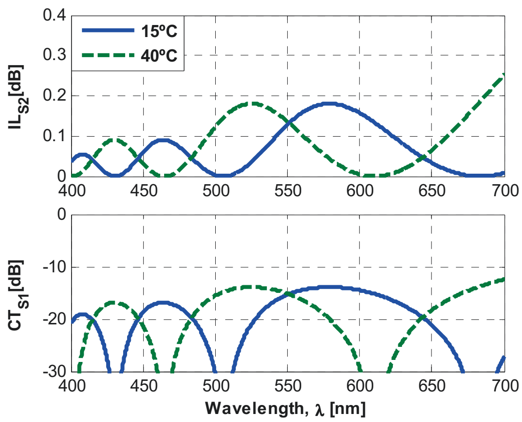


*Fig. 5: Spectral response of a LC-OS based on a 6µm TN cell of E7 material at 15ºC and 40ºC.*

As is shown in Fig. 4, the birefringence of the E7 material goes from 0.25 to 0.20 (at 500 nm), which represents a variation of 20%, in the range from 15ºC to 40ºC. This produces an important variation in the LC-OS performance. Fig. 5 shows the $IL$ and $CT$ of a 1×2 LC-OS based in a TN cell of 6 µm and E7 material at 15ºC and 40ºC. It can be seen that there is not significant variation in the maximum values of $IL$ and $CT$. Maximum $IL$ goes from 0.18 dB at 15ºC to 0.25dB at 40ºC and the maximum $CT$ goes from -13.9 dB at 15º to -12.5 dB at 40º. However, there are important variations at specific wavelengths, or channels, due to the shift of the Mauguin minima, which are traduced in output power variations. For example, the $IL$ at 700 nm has a variation up to 0.25 dB, which may not be very important. But, the $CT$ at 510, 620 and 680 nm has variations of up to 15 dB, which causes an important instability in the $S_1$ output port (in its inactive state).

## 4. Achromatic Polarization Rotator Design

In this section, an achromatic PR design, based on the scheme of Fig. 6, is presented, in order to improve the performance of the LC-OS previously analyzed. Two nematic LC cell, one NH and the other TN, with E7 material, 6 µm thickness and 90º twist (for the TN cell) are considered. As well as an $x$-polarized input beam. And the losses are neglected. Then, from Eq. (2) to Eq. (4), the transfer function of $Ty$ is given by the element [1,2] of the transfer matrix:

$$W_1 = W_H(\alpha_H) W_T(\alpha_T) \tag{9}$$

The objective of the design process is to find the best azimuth angle of each LC cell ($\alpha_H$ and $\alpha_T$) to produce the optimum response in the VIS range. The optimization is performed by using a Genetic Algorithm (GA). The random nature of the GA increments the possibility of finding a global minimum, moreover it allows implementing black-box function and the LC experimental characteristics, which can be discontinuous and non-differentiable, as part of the objective function. The proposed optimization problems consider only the $c$-axis orientation of each LC cell, $x = [\alpha_H, \alpha_T]$, see Fig. 6, and minimizes the next objective function:

$$F_{obj}(x) = \int_{400nm}^{700nm} \left|1 - T_y(x)\right| d\lambda \tag{10}$$

The searching time was 5seg and the optimal values are $\alpha_H = 15.78°$ and $\alpha_T = 15.78°$, obtaining $Ty \geq 98.33\%$ (at

15 ºC). This result, which uses only 2 LC cells, is better than the one reported in [11] ($Ty \geq 97.8\%$) and comparable to the one reported in [12] ($Ty \geq 98.87\%$), both based on three stages. The PR performance can be improved even more using 3 LC cells (one TN between two NH) but the experimental losses would increase. In the optimization has also been considered that both angles were equal. This greatly simplifies construction of the device, and also allows joining both cells into a single one, which reduce the losses caused by using two cells instead of one.

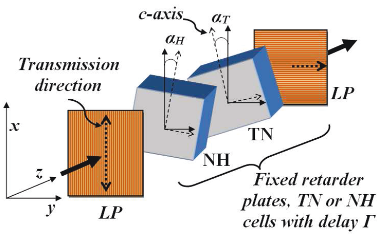


*Fig. 6: Achromatic polarization rotator scheme, with 2 stages, where NH and TN cells have 6μm thicknesses and E7 LC material, and the TN cell has 90 º twist angle. From the optimization process is obtained that $\alpha_H = \alpha_T = 15.78º$.*

## 5. Broadband 1×2 LC Optical Switch with low Thermal Dependence

The proposed 1×2 LC-OS scheme is shown in Fig. 7. While its *IL* and *CT* at 15ºC and 40ºC are shown in Fig. 8. It is can be seen that, at a given temperature, the *IL* and *CT* have a more uniform response, than the non-optimized LC-OS (see section 3). The *CT* of the optimized design is < -17.7 dB in the VIS with a maximum variation of 4.4 dB in the temperature range from 15ºC to 40ºC, while the non-optimized design has variations of more than 15 dB in the same temperature range with *CT* < -12.7 dB.

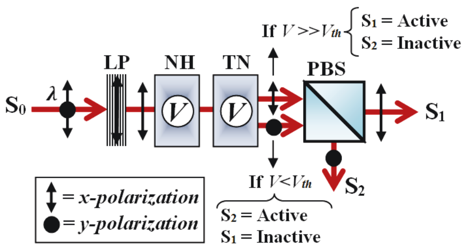


*Fig. 7: Scheme of a 1×2 LC optical switch with the optimized PR composed by a NH cell and a TN cell, both of E7 material, 6 μm thicknesses and 17º azimuth angles.*

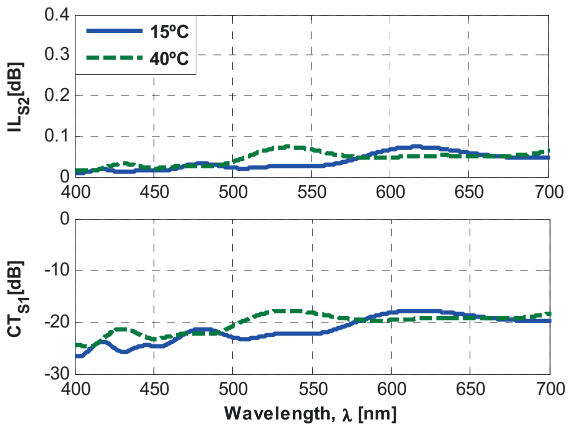


*Fig. 8: Spectral response of a LC-OS based on the optimized PR at 15ºC and 40ºC.*

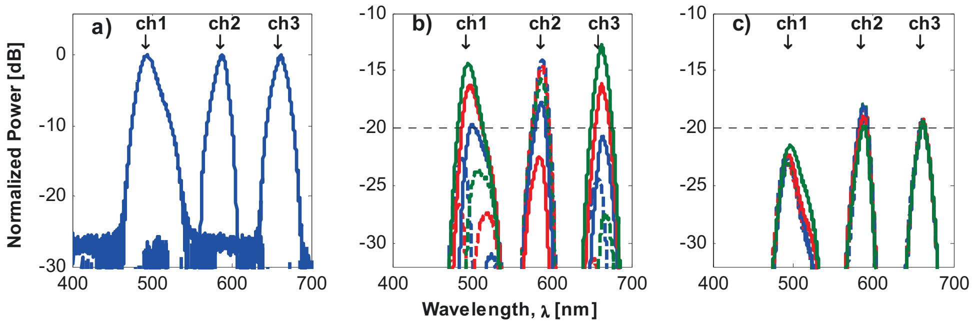


*Fig. 9: a) Input spectrum of a 3-channels system with ch1 =487 nm, ch2 = 579 nm and ch3 = 652 nm, and the simulation of the inactive output (S1) power using: b) a 1×2 LC-OS based in a single TN cell and c) a 1×2 LC-OS based the proposed design, at 15ºC (blue dashed line), 20ºC (red dashed line), 25ºC (green dashed line), 30ºC (blue solid line), 35ºC (red solid line) and 40ºC (green solid line).*

In the Fig. 9, the operation of both switches is simulated with a 3-channels system in the temperature range from 15ºC to 40ºC, in order to demonstrate the influence of those temperature variations in the inactive port. The experimental spectrums of LED sources are considered, with central wavelengths at 487, 579 and 652 nm for the channels $ch_1$, $ch_2$ and $ch_3$, respectively (Fig. 9.a). The Fig. 9.b and 9.c show the power variation at $S_1$, when it is the inactive port, for the LC-OS based in a single TN cell (non-optimized), Fig. 2 scheme, and for the proposed LC-OS based on the optimized PR, Fig. 7 scheme, respectively.

In the Fig. 9b and Fig. 9c it is shown that, with the non-optimized LC-OS the different channels have power variations of about 16 dB, in the considered temperature range. While with the optimized LC-OS the power variations are less than 2 dB, with values of about 20 dB. For example, with the non-optimized design at 20ºC (red dashed lines), the channels $ch_1$, $ch_2$ and $ch_3$ have -26.7, -14.6 and -31.4 dB of power, while at 35ºC (red solid line) those channels have -16.34, -22.55, -16.22 dB of power, which represent variations of 10.4, 7.9 and 15.18 dB, respectively. On the other hand, in the same temperature range (20º to 35ºC), with the proposed design the power variations are less than 0.9 dB.

## 6. Conclusions

The optimized design of a broadband 1×2 LC-OS has been presented. This device is capable of switching optical signals from the input port to one of its output ports with a uniform response, with $IL$ < 0.80 dB and $CT$ < -17.78 dB in the range from 400 nm − 700 nm. In the same range the non-optimized design presents $IL$ < 0.18 dB and $CT$ < -13.9 dB, with many minimum and maximum (non-uniform response). It is also demonstrated that the proposed design has a low thermal dependence in the range from 15ºC to 40ºC, with $CT$ variations of less than 2 dB.

The proposed design allows a significantly improvement of the spectral response of 1×2 LC-OSs in a broadband range (400 nm–700 nm). Which is required for implementing POF-WDM networks [1], and it can be achieved without highly complicating their construction and using commercially available LC cells (fixed thicknesses). Since the LC cells have the same azimuth angle, they are easy to join in a single device, reducing the losses caused by adding another LC cell.

## Acknowledgements

This work has been sponsored by the Spanish Economy and Education Ministries through grants (Ref. TEC2012-37983-C03-02 and Ref. PRX12/00007).

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