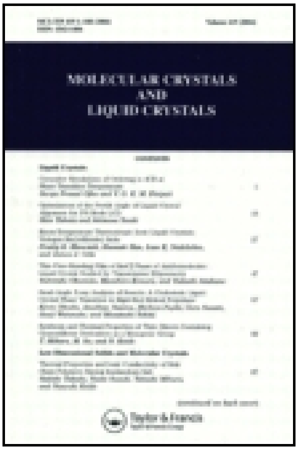

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A Switchable Optical Add-Drop Multiplexer using Ion-Exchange Waveguides and a POLICRYPS Grating Overlayer

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We propose a novel add-drop multiplexer for dense wavelength division multiplexing optical communications (DWDM) operating in C band (1530–1565 nm). The device has been designed for channel in-diffused glass waveguides. The device is switchable because a POLICRYPS (POlymer LIquid CRYstal Polymer Slices) based grating is deposited on top of the wider bimodal waveguide. At our knowledge this is the first example of switchable add-drop multiplexer.

Keywords: composite materials; gratings; integrated optics; liquid crystals; optical add-drop multiplexers; polymers

INTRODUCTION

One of the key components in wavelength-division multiplexed (WDM) systems is the optical add-drop multiplexer consisting in a four-port device used to add and/or drop a particular channel. One possible configuration of this device is composed of a null coupler with a tilted grating in its waist [1]. A null coupler is composed by two different waveguides which progressively converge into one another to form the waist. An adiabatic mode transformation takes place along the coupler arms and their waist [2,3]. Contra-directional coupling and add-drop function can be obtained with a tilted grating in the waist.

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In this paper a novel add-drop multiplexer is presented, made of ion-exchange optical waveguides and a POLICRYPS tilted phase grating placed on the top of the null coupler waist. POLICRYPS gratings are new structures made of slices of polymeric material separated by liquid crystal films, which can be switched by applying an electric field [4]. In fact the applied field induces a reorientation of the liquid crystal molecules thus changing their refractive index. As a consequence the phase grating can be switched on and off by controlling the refractive index mismatch between the liquid crystal and polymer slices. Such gratings can be used to obtain switchable add-drop multiplexers allowing to switch from a condition where the device is transparent to the crossing signals to another condition where the device acts as a filter of the crossing signals. Different geometry structures have been designed in particular in order to minimize structural losses. The optimized structure consists of double-ion-exchange waveguides, K^+-Na^+ and Ag^+-Na^+, with an index change at the surface of 0.05, width of 10 μm, thickness of 3.5 μm and buried with a diffusion depth of 1 μm. The grating has a thickness of 1 μm, step of 508 nm and a tilt angle of 3.6°.

PRINCIPLE OF WORKING

The add-drop has a symmetrical structure where three regions can be distinguished [5]. The first input region (Fig. 1) is composed of two antisymmetrical single-mode ion-exchange waveguides which merge in the second region to form one bimodal waveguide. A periodic grating made of POLICRYPS [6,7] tilted with respect to the light propagation direction is deposited on the surface of the second region acting as a switchable overlayer. A third output region has a specular shape of

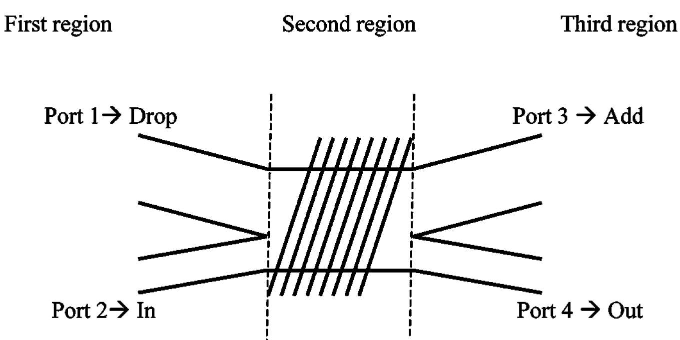

FIGURE 1 Structure of the proposed optical add-drop multiplexer.

the first region with two single-mode antisymmetrical waveguides. If a multiwavelength light beam enters the device from the narrower waveguide (Port 2), the odd mode of the central region is mostly excited and is routed into the lower output port (Port 4). For a particular wavelength (λ-channel) the grating reflects the odd mode and at the same time couples the power into the even mode.

Hence the reflected even mode is routed into Port 1 realizing the "Drop" function. If a light beam with a particular λ-channel enters the device from Port 3 instead, the even mode is excited in the central region. Then the even mode is reflected and converted into the odd mode by the grating, thus the power is routed into Port 4, thus realizing the "Add" function.

The innovative characteristic of this device is the possibility to turn the "Add-drop" function on and off. Such a switching behaviour is due to the POLICRYPS grating, whose index modulation can be controlled by varying the voltage applied. The POLICRYPS grating is in Off-state (Fig. 2a) when there is a matching between the refractive indices of the polymer and of the liquid crystal ($n_P = n_{LC}$), thus the device is transparent. The grating is in On-state (Fig. 2b) when there is a mismatch between the polymer and the liquid crystal refractive indices. In the On-state the λ-channel which is resonant with the grating period, is reflected and then a mode conversion occurs.

STRUCTURE OF THE DEVICE

The designed device is made of ion-exchanged waveguides in BK7 glass [8]. In particular the double-ion-exchange process, K^+-Na^+ and Ag^+-Na^+ is used to obtain optical waveguides with an index change at the glass surface of about 0.05. Such a refractive index change allows to combine the optical waveguides with the overlaying POLICRYPS gratings (Fig. 3). The waveguide refractive index profile has been figured out by means of a BPM CAD. The first and third regions have been designed in order to have a crosstalk of –30 dB between even and odd modes in the second region, whether controlling the device from Port 1 or from Port 2. Moreover the geometric characteristics of the waveguides and the grating have been designed in order to obtain a device which can be used in fiber optic communication systems [9].

The ion-exchange waveguide of the central region of the device has a width of 10 μm, a thickness of 3.5 mm and is buried with a diffusion depth of 1 μm after thermal annealing. The waveguide is bimodal over the entire C band. A 1 μm thick and 8 μm wide POLICRYPS grating is deposited on top of the waveguide surface. The period of the grating

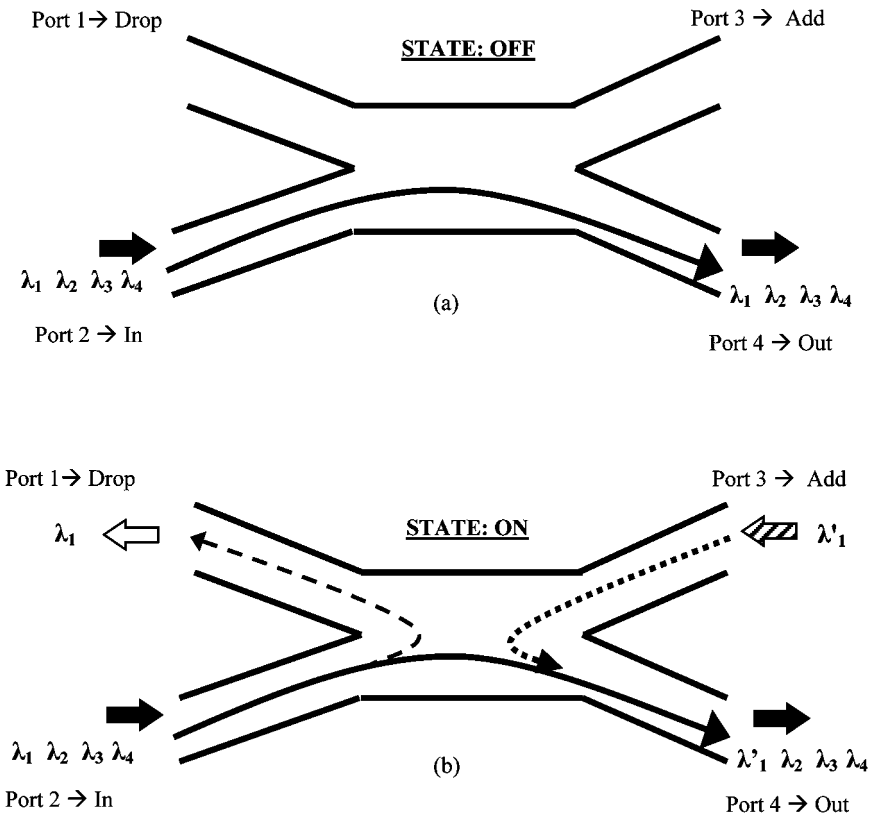

FIGURE 2 Add-drop working principle. In the Off state (a) all the optical channels (λ) pass through the device from Port 2 (In) to Port 4 (Out). In the On state (b) a channel (λ_1) is extracted and routed in Port 1 (Drop) and at the same time is possible to insert a channel (λ_1') in Port 3 (Add) and routing it in Port 4 (Out).

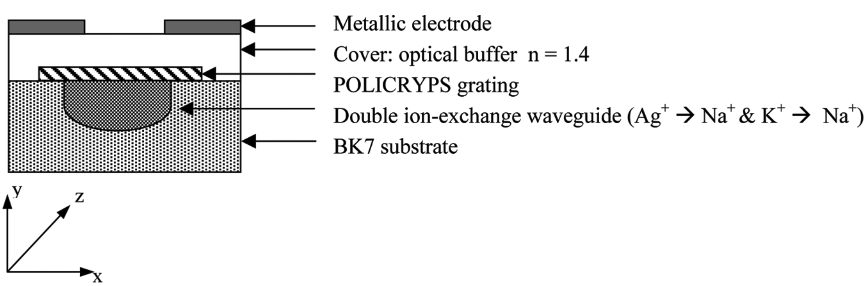

FIGURE 3 Add-drop central section.

is 508 nm, with a tilt angle with respect to the propagation direction of 3.6°. From the numerical analysis carried out it turned out that the best performances are obtained by using POLICRYPS made of a polymer with a refractive index of 1.52 and the liquid crystal 5CB which shows an ordinary refractive index of 1.5108 and an extraordinary one of 1.6807 at 1550 nm and 20°C. Finally there is a low refractive index optical buffer to isolate the electrodes, as depicted in Figure 3.

A proper numerical model has been implemented to determine the structural losses due to the discontinuity of the refractive index in the propagation direction due to the presence of the grating placed on the ion-exchange waveguide.

NUMERICAL MODEL

The grating behaves as a scattering region breaking the mode orthogonality redistributing their optical power. The study is carried out for a grating in the bimodal region for both the even and the odd mode [10,11].

The electric field in the bimodal region can be expressed as (see Fig. 4):

$$E = \Big\{(F_1(z)e^{-j\beta_{g1}z} + G_1(z)e^{+j\beta_{g1}z}) \cdot \Psi_{\beta_{g1}}(x) + (F_2(z)e^{-j\beta_{g2}z} + G_2(z)e^{+j\beta_{g2}z}) \cdot \Psi_{\beta_{g2}}(x)\Big\} \tag{1}$$

where:

$\Psi_{\beta g0}, \Psi_{\beta g1}$ are the transversal distributions of even mode (0) and odd mode (1).

β_{g0}, β_{g1} are the phase or propagation constants of even and odd modes.

$\boldsymbol{F}_1, \boldsymbol{F}_2$ are the amplitudes of even and odd modes propagating along Z direction.

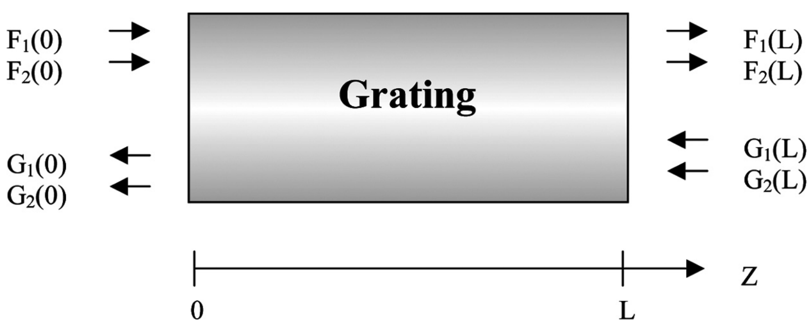

FIGURE 4 Scheme of the grating region for the numerical model.

$\boldsymbol{G}_1, \boldsymbol{G}_2$ are the amplitudes of the counter propagating even and odd modes.

The evolution along Z of $\boldsymbol{F_1}$, $\boldsymbol{F_2}$, $\boldsymbol{G_1}$, $\boldsymbol{G_2}$ is described by the differential equation system derived from the coupled mode theory:

$$\begin{aligned}
\frac{dF_1}{dz} &= -jk_{11}G_1(z)e^{j2\Delta\beta_1 z} - jk_{12}G_2(z)e^{j(\Delta\beta_1+\Delta\beta_2)z} \\
\frac{dF_2}{dz} &= -jk_{12}G_1(z)e^{j(\Delta\beta_1+\Delta\beta_2)z} - jk_{22}G_2(z)e^{j2\Delta\beta_2 z} \\
\frac{dG_1}{dz} &= jk_{11}^*F_1(z)e^{-j2\Delta\beta_1 z} + jk_{12}^*F_2(z)e^{-j(\Delta\beta_1+\Delta\beta_2)z} \\
\frac{dG_2}{dz} &= jk_{12}^*F_1(z)e^{-j(\Delta\beta_1+\Delta\beta_2)z} + jk_{22}^*F_2(z)e^{-j2\Delta\beta_2 z}
\end{aligned} \tag{2}$$

where $\Delta\beta_i = \beta_{gi} - K_B = \beta_{gi} - \pi/\Lambda$, with $(i = 1,\ 2)$, is the resonance Bragg condition between the optical wave and the grating. β_{gi} is the propagation constant of the i mode (with $i = 0$ even and $i = 1$ odd) and Λ is the grating period.

In order to solve the differential equation system (2) is primarily necessary to figure out k_{11} k_{22} k_{12} coefficients given by the following integrals:

$$\begin{aligned}
k_{11} &= \frac{\omega\varepsilon_0}{4}\int_S \Delta\varepsilon_{+1}(x)\cdot\Psi_{\beta_{g1}}^2 dxdy \\
k_{12} = k_{21}^* &= \frac{\omega\varepsilon_0}{4}\int_S \Delta\varepsilon_{+1}(x)\cdot\Psi_{\beta_{g1}}\cdot\Psi_{\beta_{g2}}^* dxdy \\
k_{22} &= \frac{\omega\varepsilon_0}{4}\int_S \Delta\varepsilon_{+1}(x)\cdot\Psi_{\beta_{g2}}^2 dxdy
\end{aligned} \tag{3}$$

where Ψ_i is a function *f(x,y)* symbolizing the mode i of the waveguide calculated by means of a BPM, considering the grating in matching condition ($n_{cl} = n_p$). k_{11} k_{22} k_{12} are the coupling coefficients which take into account the reflection and the power coupling due to the grating. S is the region with the grating in the XY plane.

The dielectric constant of a grating tilted along the x axis can be written as:

$$\Delta\varepsilon_r(x,z) = (\Delta\varepsilon_{+1})_{tilted}\cdot e^{-j(2\pi/\Lambda g)z} \tag{4}$$

with:

$$(\Delta\varepsilon_{+1})_{tilted} = \Delta\varepsilon_{+1}\cdot e^{-j((2\pi/\Lambda)\tan\theta)\cdot x} \tag{5}$$

The mode powers in the central region can be calculated by writing equations (2) in matrix form. Hence, the output powers can be figured out by combining the mode powers with the coupling conditions applied to the ports of the Y junction.

The equations (2) can be written as:

$$\begin{pmatrix} F(L) \\ G(L) \end{pmatrix} = P(0,L)\begin{pmatrix} F(0) \\ G(0) \end{pmatrix} = \begin{pmatrix} P_{FF} & P_{FG} \\ P_{GF} & P_{GG} \end{pmatrix}\begin{pmatrix} F(0) \\ G(0) \end{pmatrix} \tag{6}$$

with:

$$P(0,L) = \exp(S_1 L)\exp(S_2 L); \tag{7}$$

$$S_1 = \begin{pmatrix} j\Delta\beta_1 & 0 & 0 & 0 \\ 0 & j\Delta\beta_2 & 0 & 0 \\ 0 & 0 & -j\Delta\beta_1 & 0 \\ 0 & 0 & 0 & -j\Delta\beta_2 \end{pmatrix}; \tag{8}$$

$$S_2 = \begin{pmatrix} -j\Delta\beta_1 & 0 & -jk_{11} & -jk_{12} \\ 0 & -j\Delta\beta_2 & -jk_{12} & -jk_{22} \\ jk_{11}^* & jk_{12}^* & j\Delta\beta_1 & 0 \\ jk_{12}^* & jk_{22}^* & 0 & j\Delta\beta_2 \end{pmatrix} \tag{9}$$

The powers coupled to the modes in the central region can be calculated as:

$$Pout_{TXij} = |F_i(L)|^2 = |(P_{FF} - P_{FG}P_{GG}^{-1}P_{GF})_{ij}|^2 \cdot |F_j(0)|^2 \tag{10}$$

$$Pout_{RKij} = |G_i(0)|^2 = |(P_{GG}^{-1}P_{GF})_{ij}|^2 \cdot |F_j(0)|^2 \tag{11}$$

where:

$Pout_{TXij}$ is the power of the transmitted *i*-mode excited by the *j*-mode propagating through the waist of the null coupler,

$Pout_{RXij}$ is the power of the reflected *i*-mode excited by the *j*-mode propagating through the waist of the null coupler.

The powers coming out from the device ports are given by the following expressions:

$$Pout_{portm} = (Pout_{BKii} + Pout_{BKij}) + K_l \cdot (Pout_{BKjj} + Pout_{BKji}) \tag{12}$$

$$Pout_{portr} = (Pout_{TXii} + Pout_{TXij}) + K_l \cdot (Pout_{TXjj} + Pout_{TXji}) \tag{13}$$

where:

K_l is the coupled parameter given by the over position integral between the field excited at the bimodal region input and the l-mode guided in the bimodal region ($l = 1$, 2);

$Pout_{portm}$ is the output power from port m (m = 1, 2);
$Pout_{portr}$ is the output power from port r (r = 3, 4).

EVALUATION OF THE STRUCTURAL LOSSES

Reflections must be taken into account because the grating causes a discontinuity of the refractive index profile along the propagation direction.

The electric field E in the three regions can be written as (Fig. 5):

$$E_{left} = (A_1 e^{-j\beta_1 z} + B_1 e^{+j\beta_1 z})\Phi_1 + (A_2 e^{-j\beta_2 z} + B_2 e^{+j\beta_2 z})\Phi_2 \quad (14)$$

$$E_{grating} = (F_1 e^{-j\beta g_1 z} + G_1 e^{+j\beta g_1 z})\Psi_1 + (F_2 e^{-j\beta g_2 z} + G_2 e^{+j\beta g_2 z})\Psi_2 \quad (15)$$

$$E_{right} = (C_1 e^{-j\beta_1 z} + D_1 e^{+j\beta_1 z})\Phi_1 + (C_2 e^{-j\beta_2 z} + D_2 e^{+j\beta_2 z})\Phi_2 \quad (16)$$

The fields outside and inside the grating region can be interrelated in order to evaluate the coupling losses and the reflection effects. In particular overlapping integrals to get the two matrices T_{ij} and U_{ij} have been evaluated respectively for $E_{left} \rightarrow E_{grating}$ and for $E_{grating} \rightarrow E_{left}$:

$$T_{ij} = \frac{\beta_{gi}}{2\omega\mu_0} \iint \Psi_i(x,y) \cdot \Phi_j(x,y) dxdy \quad (17)$$

$$U_{ij} = \frac{\beta_i}{2\omega\mu_0} \iint \Phi_i(x,y) \cdot \Psi_j(x,y) dxdy \quad (18)$$

where Φ_i is the ith-mode in the waveguide of the central region without the grating and Ψ_i is the ith-mode in the waveguide of the central region with the grating.

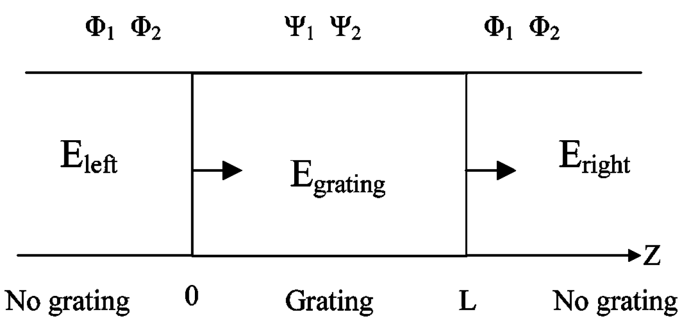

FIGURE 5 Sketch of the grating and no grating regions for the evaluation of the structural losses.

From equation (6) it is possible to evaluate the mode powers in a different form:

$$\begin{pmatrix} F_1(0) \\ F_2(0) \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} \tag{19}$$

$$\begin{pmatrix} B_1 \\ B_2 \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} \\ U_{21} & U_{22} \end{pmatrix} \begin{pmatrix} G_1(0) \\ G_2(0) \end{pmatrix} \tag{20}$$

obtaining for the reflected power:

$$(P_{outBK})_{ij} = |(UP_{GG}^{-1}P_{FG}T)_{ij}|^2 (P_{in})_j \tag{21}$$

and for the transmitted power:

$$(P_{outTX})_{ij} = |(U[P_{FF} - P_{FG}P_{GG}^{-1}P_{GF}]T)_{ij}|^2 (P_{in})_j \tag{22}$$

RESULTS AND DISCUSSION

The performances of the simulated add-drop have been evaluated by looking at the power spectra of the output ports.

The spectral curves plotted in Figure 6 have been obtained by considering a grating index modulation by $3{\cdot}10^{-3}$. The curve in solid line is the spectrum of the output power of Port 1 and represents the

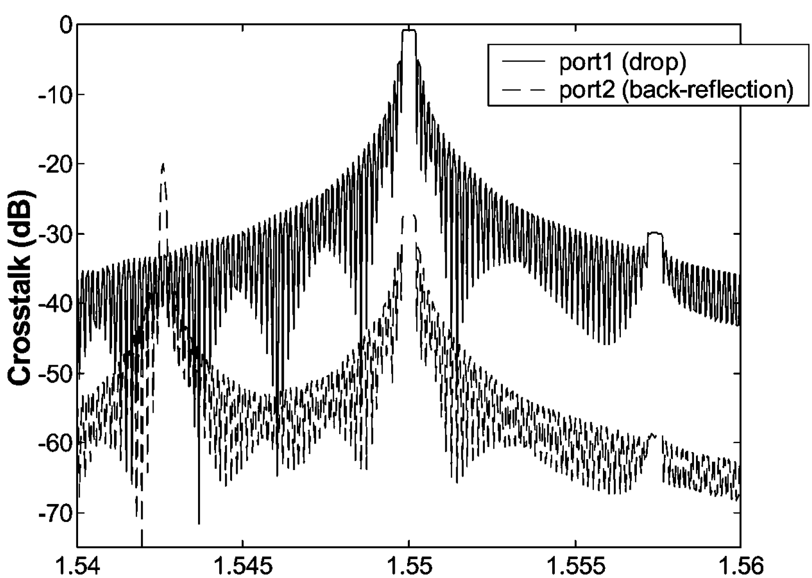

FIGURE 6 Reflection power spectra at the drop-port (solid line) and at the input port (dashed line).

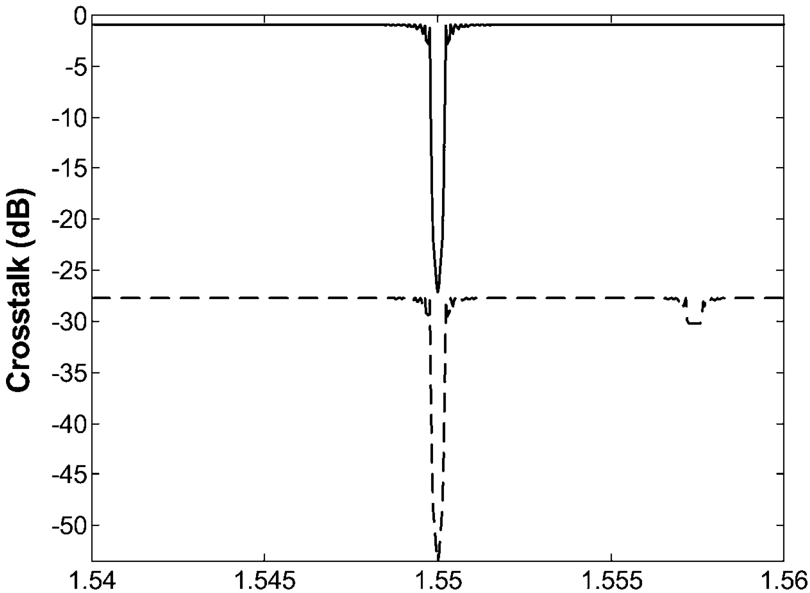

FIGURE 7 Transmitted power spectra at the output port (solid line) and at the add-port (dashed line).

optical spectrum of the "Drop" function. The extracted channel is a λ-channel at 1550 nm. The "Drop" flat band at 3 dB is 1 nm and the losses due to the index profile non-uniformity along Z are –0.73 dB. Instead the dashed line is the signal power spectrum coming out from Port 2 and represents the reflected power at the input port. It is clearly observable that all the back-reflected power is less than –30 dB except the peak of –20 dB at the wavelength of 1542.6 nm. From the drop curve it is possible to extrapolate the crosstalk values for several channel spacings for WDM optical system applications.

Figure 7 shows the transmitted power spectra. The solid line is the power coming out from Port 4 and it is clearly visible the dropped signal at 1550 nm and a structural loss of –0.91 dB. The dashed line represents the power, which is inevitably coupled at Port 3. Although such coupled power is less than –27 dB and therefore can be neglected.

In Table 1 the performance of the device for different grating index modulations are reported. In particular the table includes the cross-talk values for different channel spacings, the reflected power at the input port at 1542.6 nm and at 1550 nm, the losses of the output dropped signal and the losses which each signal suffers both in On state and in Off state at the output Port 4. The drop band at –3 dB

TABLE 1 Device Characteristics for Different Grating Index Modulations

Grating index modulation	10^{-3}	$2{\cdot}10^{-3}$	$3{\cdot}10^{-3}$
Reflection (dB) at 1542.6 nm	–29	–23.5	–20
Reflection (dB) at 1550 nm	–29	–27.7	–27.7
R losses (dB) at 1550 nm	–2.18	–0.84	–0.73
T losses (dB)	–0.91	–0.91	–0.91
Drop band at 3 dB (nm)	<0.2	0.4	1
Crosstalk (dB) at 0.4 nm	–16	–11.3	–8.1
Crosstalk (dB) at 0.8 nm	–22	–16	–13
Crosstalk (dB) at 1.6 nm	–27.7	–21.5	–18
Crosstalk (dB) at 3.2 nm	–33.4	–27.5	–24
Crosstalk (dB) at 6.4 nm	–39.6	–33.7	–30

can be lower than 0.2 nm for a grating index modulation of 10^{-3}. This result indicates that the device can be employed even for dense WDM optical communication systems. The aforesaid grating index modulation can be obtained with small variations of the applied voltage, typically some 10 mV from the bias at about 3 V [7]. From Table 1 it is also possible to see that using a grating index modulation of $3{\cdot}10^{-3}$ the device shows a –3 dB bandwidth of 1 nm, losses of –0.73 dB, crosstalk of –18 dB for a spacing channel of 1.6 nm, and crosstalk of –24 dB for a spacing channel of 3.2 nm. The reflected power at the input port at the wavelength of 1542.6 nm is about –20 dB and about –27.7 dB at 1550 nm. Results are also given for a grating index modulation of $2{\cdot}10^{-3}$.

CONCLUSIONS

We have reported a novel integrated switchable add-drop multiplexer with a grating length of 5 mm and a total length for the device of 10 mm. The most important device feature is the possibility to change grating index modulation of the device by means of the electro-optic effect in the liquid crystal layers of the POLICRYPS.

The designed switchable add-drop multiplexer using a POLICRYPS grating performs with a crosstalk of –22 dB and with just 0.8 nm wavelength spacing as used in DWDM optical communication systems.

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