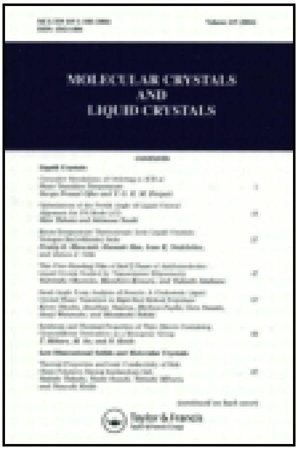

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Tunable T-Shaped Waveguide in Two Dimensional Photonic Crystals Based on Liquid Crystals

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In the last years, in order to achieve active tuning of photonic crystals devices, the possibility to use liquid crystal inside photonic crystals has been explored.

On this line of argument, in this paper, we numerically investigate a tunable T-shaped waveguide diplexer, based on a two-dimensional square lattice photonic crystal composed of silicon rods in a liquid crystals. We prove that complete splitting of the entire input wavelengths range in two sub-ranges symmetrical with respect to the middle (switching) wavelength, and propagating in right and left arms respectively, can be achieved. Moreover, changing the refractive index of liquid crystals by electro-optical effect, a tuning of switching wavelength of about 60 nm can be obtained.

Keywords: liquid crystals; photonic crystals; tunable diplexer, waveguide

I. INTRODUCTION

Photonic crystals (PhCs) have attracted much attention from both fundamental and practical viewpoints, because novel concepts such as photonic band gaps have been predicted and various new applications of photonics crystals have been proposed [1–3]. The use of silicon

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($\varepsilon = 11.9$) as base material for 2D photonic crystals seems natural because of its high refractive index at the communication wavelengths and the possibility of exploiting the well-known micro-fabrication technologies [4,5]. Moreover, recently, silicon-based photonic integrated circuits have achieved significant progress [6].

An ideal two-dimensional (2D) PhC consists of a periodic array of infinitely long pores or rods. Simple defects lines in a PhC form very effective optical waveguides, by introducing dispersion relations in photonic band gaps that can be satisfied only by waves propagating along the defect lines [3]. One of the most important optical properties of PhCs is that the waveguide dispersion relations can be tailored, allowing for many non-conventional applications such as guiding and processing of the light signal.

The band structure and light propagation properties are fixed by the geometry of the PhC and cannot be modified after the fabrication process, whereas for many possible applications, the tuning of PhCs properties during operation would be very desirable, for example, for optical switches, tunable filters, wavelength division multiplexing, channel add-drop filtering and reconfigurable optical networks.

In order to design filters, diplexers and multiplexers, different kind of defects, and different optimisation approaches have been adopted [7–9]. A further improvement for such devices is the tuning capability. Recently, tunable light propagation in Y-shaped waveguides in 2D PhC composed of narrow-band semiconductor (InSb) and based on thermo-optical effect has been proposed [10].

In order to overcome the lack of mechanism for switching ad filtering in silicon based PhCs, a very promising approach in order to achieve active tuning of the photonic properties can be obtained by using liquid crystal properties inside photonic crystals.

A variety of physical phenomena make liquid crystals (LCs) one of the most interesting subject of modern fundamental science. At the same time, their unique properties, which give rise to enhanced optical anisotropy and sensitivity to external fields, could be exploited in a large number of practical applications. The main feature of LCs is the high sensitivity of their optical response to an applied electrical field. Liquid crystals have effective electro-optic coefficients orders of magnitude larger than their solid state counterparts, due to their anisotropy and large electric-field induced molecular reorientation. These properties, combined with their ability to be micromanipulated, their low cost and the possibility for integration with silicon circuit technology make LCs particularly attractive in designing photonic devices, whenever compactness, complexity, and low cost are more important requirements than switching speed [11–18].

The idea to use liquid crystal properties inside photonic crystals to obtain tunable photonic properties goes back to the theoretical predictions by Bush and John [19] and the experimental work by Yoshino *et al*. [20]. These works considered to fill the liquid crystal into the voids of an artifical opal or an inverted colloidal crystal, respectively. Since, then, many other photonic crystal systems containing liquid crystals were developed [21,22]. Recently, tunable Y-shaped waveguides adopting liquid crystals as linear defect in a GaAs substrate [22] has been proposed. In this device the light can propagate on one side or on both sides of Y-shaped waveguides depending on the orientation of liquid crystals. The main drawback of this device is that a significant frequencies range of light is coupled into both output waveguides.

In this paper, the design of a T-shaped diplexer based on silicon PhCs in liquid crystals is presented. The aim of our design is to eliminate the wavelength crosstalk between two outputs of T-junction. In other words, to split the entire input wavelengths range in two disjoint sub-ranges propagating in right and left arms of T-shaped PhC waveguide, respectively. Furthermore, we investigate the possibility to tune the switching point by means the electro-optic effect of liquid crystals.

II. DESIGN OF PHC DIPLEXER

The proposed device is a T-shaped two dimensional square lattice photonic crystal composed by silicon ($\varepsilon = 11,9$) rods in E7 nematic liquid crystals.

A photonic crystal arranged in a square lattice has a band gap for TM polarization (electric field parallel to the rods). The band-gap depends on the rods radius and on the index contrast between the background and the rods material. The first step of our procedure is to individuate the rod radius of the basic structure in order to get the maximum gap. We suppose that, without any applied field, the director alignment is perpendicular to the rods. The gap-map, i.e., the forbidden frequencies range versus the radius of the silicon rods, obtained by using a commercial software (BandSolve simulator by RSoft), is shown in Figure 1. As we can see, for a two dimensional square lattice photonic crystal composed by silicon ($\varepsilon = 11{,}9$) rods in E7 nematic liquid crystals ($\varepsilon_{LC} = 2.25$), for the TM polarization, $\Delta\omega = (0{,}3023 \div 0{,}2557) \times 2\pi c/a$ is the widest band gap and it is obtained with the rod radius $R = 0.228a$, where a is the lattice constant.

A defect into the PhC creates a waveguide, i.e. a sort of obliged way for the light that can't propagate elsewhere. In our T-shaped

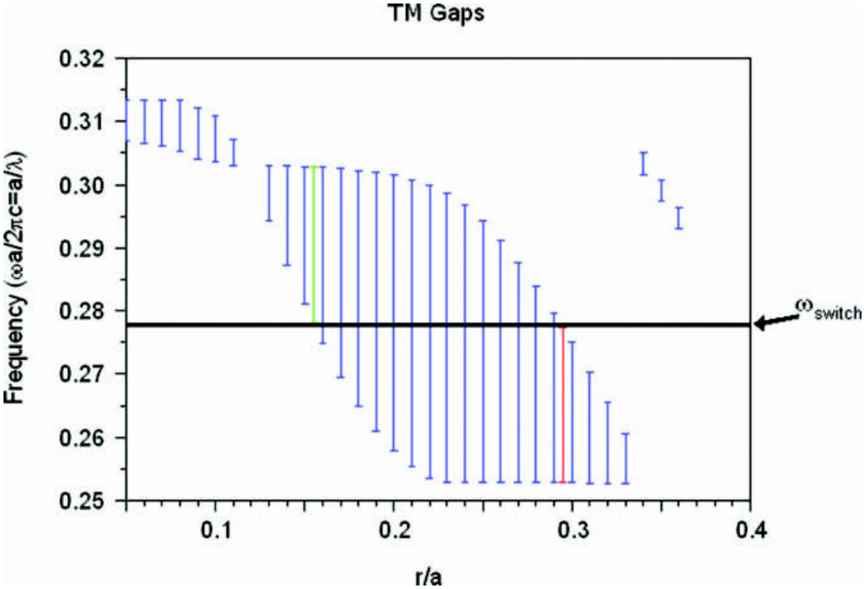

FIGURE 1 Gap map for TM polarization. The gaps (green and red bar) has been matched to have complementary gap with respect to the switching frequency: $\omega_{sw} = (0.2780) \times 2\pi c/a$.

waveguide diplexer, in order to get the biggest propagating frequencies range, the input waveguide is created by removing a row of pillars in the direction of propagation. Since our aim is to separate light of different frequencies, we design to insert two lateral branch defects a the end of the input waveguide (see Fig. 2). The crucial point of our design is to split the entire frequencies range propagating into the input waveguide in two complementary ranges, propagating into left and the right branch, respectively.

According to the gap-map in Figure 1, defining the switching frequency: $\omega_{sw} = (0.2780) \times 2\pi c/a$, if we choose the following size radius $r_1 = 0.154a$, for the left branch, we have the gap $\Delta\omega_1 = (0.30436 \div 0.2780) \times 2\pi c/a$ (green bar in Fig. 1), while choosing the size radius $r_2 = 0.294a$, for the right branch, we have the gap $\Delta\omega_2 = (0.2780 \div 0.2537) \times 2\pi c/a$ (red bar in Fig. 1). As a consequences, we expect that a mode propagating into the left branch could have frequencies only into the range $\Delta\omega_2 = (0.2780 \div 0.2537) \times 2\pi c/a$ (the complementary of the forbidden frequencies), while, a mode propagating into the right branch can have frequencies only into the range $\Delta\omega_1 = (0.3043 \div 0.2780) \times 2\pi c/a$.

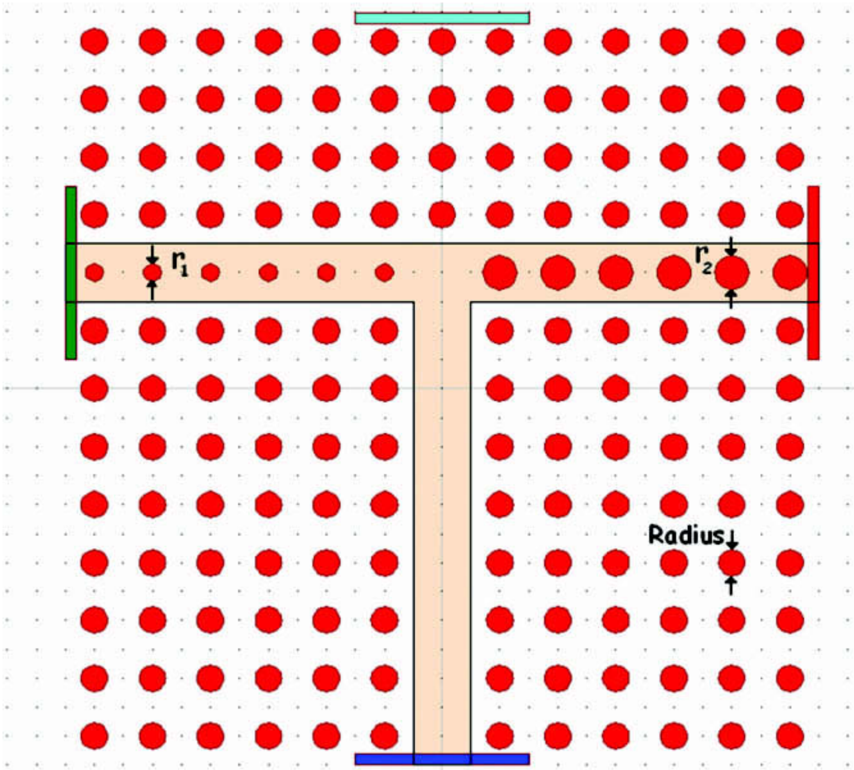

FIGURE 2 Sketch of device: blue gate indicates the input source position; red and green gates are the output windows. We suppose that LC is reoriented only into the 'pink zone' onto the defect channels.

In order to prove the previous statement, as a second step of our project, we compute the dispersion relations of the guided modes into the input, left and right waveguide. The width of the computed cell corresponds to the periodicity a of the dielectric in the direction of the guide, while the height was taken to avoid that the eigenmodes no longer depended on the cell size. Considering a cell with a central defect surrounded by four pillars ensures that the distance between the adjacent guides is sufficient so that modes localized in each guide do not appreciably couple to each other. The results are shown in Figure 3, the blue line corresponds to the guided mode in the input branch (W1); the green and red lines represents the dispersion relations for left (W2) and right waveguides (W3), respectively. We note that the guided mode (blue line) of input waveguide can support light propagation in a wide frequency range of the photonic band gap.

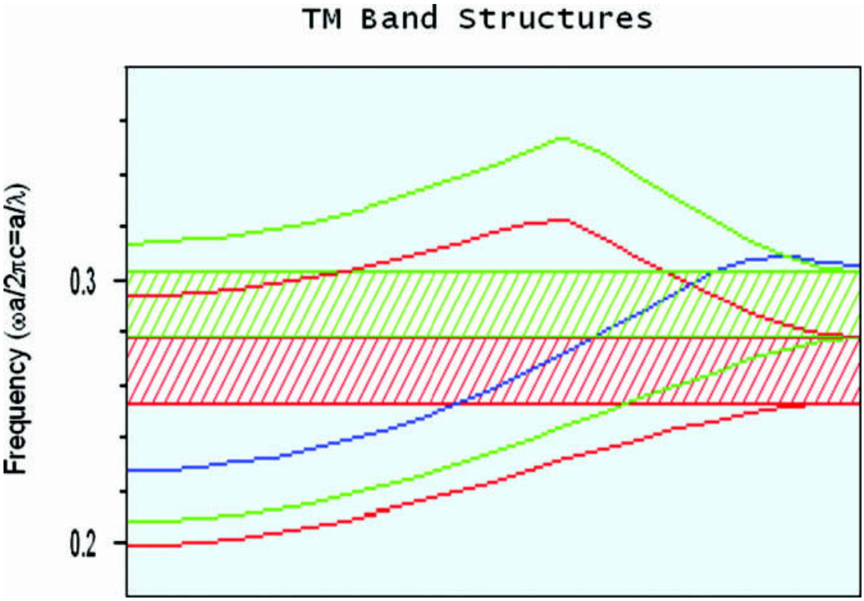

FIGURE 3 Dispersion relations of guided modes. The blue lines corresponds to input branch guided mode; the green and red lines corresponds to left and right branch guided mode, respectively.

The green line is extended only into the range $\Delta\omega_2 = (0.2780 \div 0.2537) \times 2\pi c/a$, this means that this frequencies range can propagate in waveguides W1 and W2 (left) although light can not propagate in waveguide W3 (right). The red line is extended only into the range $\Delta\omega_1 = (0.3043 \div 0.2780) \times 2\pi c/a$, this means that this frequencies range can propagate in W1 and W3, but can not propagate in W2. Therefore a complete splitting of the entire input wavelengths range in two sub-ranges symmetrical with respect to the middle (switching) wavelength, and propagating in right and left arms respectively, could be achieved.

In Figure 4, we show the electric field patterns in the T-shaped waveguides when incident light is excited at the input point of W1 waveguide. We note that for $\omega = 0.2941 \times 2\pi c/a > \omega_{sw}$ the light is propagating in the right branch (Fig. 4a), whereas for $\omega = 0.2703 \times 2\pi c/a < \omega_{sw}$ the light is propagating in the left branch (Fig. 4b).

This is the first important results of our design, being the wavelength crosstalk between two outputs of T-junction eliminated, we are able to overcome the main limitations of previous proposed devices based on liquid crystals technology [22].

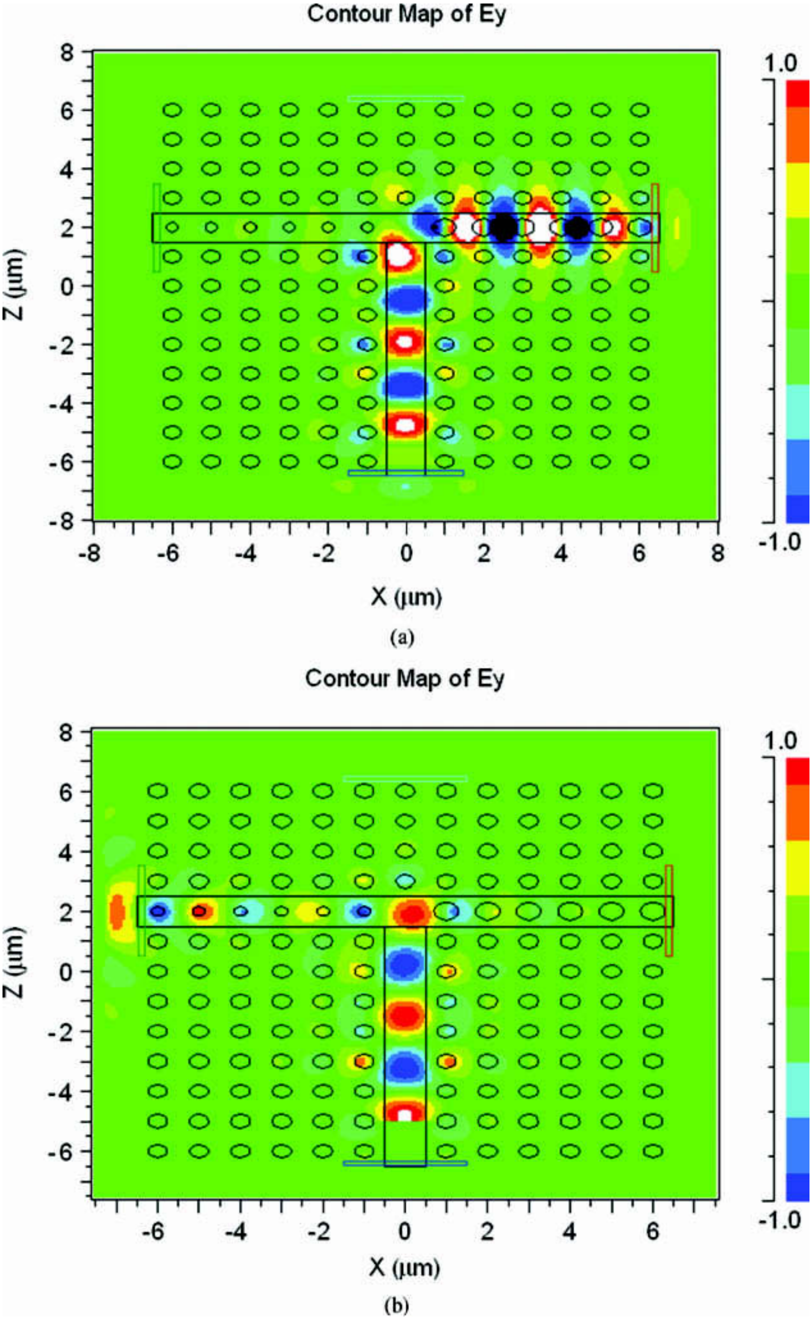

FIGURE 4 (a) Electric Field patterns for $\omega = 0.2703 \times 2\pi c/a > \omega_{sw}$, (b) Electric Field patterns for $\omega = 0.2941 \times 2\pi c/a > \omega_{sw}$.

III. TUNABLE OPTICAL PHC DIPLEXER BASED ON LIQUID CRYSTALS

In order to tune the switching frequency, in this paragraph, the variation of liquid crystals refractive index, induced by an electric field, is considered.

In 2D PhCs composed of isotropic materials, high rotational and mirror symmetry exists in wave-vector spaces, as a consequences, two modes, i.e., the transversal electric (TE) mode and the transversal magnetic mode (TM), exist. In photonic crystals composed of anisotropic materials, no symmetry generally exists; therefore none of these two classifications (TE and TM) mode could be done. However, in some configuration, the classification of TE and TM can be valid, too.

In our initial configuration, we suppose that, without any applied field, the molecules of NLC are aligned perpendicular to the propagation direction, i.e., perpendicular to the rods. Therefore, TM mode (light wave having the electric field parallel to the rods) being perpendicular to the director of the liquid crystal, 'sees' ordinary refractive index.

Of course, the refractive index of liquid crystals seen by TM mode can be changed under the influence of an electric field. The realisation of electro-optical devices requires the deposition of thin transparent electrodes. As rather usual in LC displays, we consider ITO (indium tin oxide) as the electrode material. In order to apply the electric field along the direction of rods, we suppose that ITO electrode can be deposited on top and bottom of 2D-PhC. Moreover, in order to apply the electric field only along the defects (pink zone in the sketch of device in Fig. 1), only a stripe of ITO onto the light pink zone should be realised.

Applying an electric field between the two ITO electrodes, the LC molecules tilt in the plane containing the direction of light wave electric field and the propagation direction of light, therefore for TM wave a pure modulation is achieved, the polarisation state being maintained. Light wave having electric field parallel to the director of liquid crystal sees extraordinary refractive index. For intermediate position of director, the refractive index experienced by TM mode is given by the following general relation:

$$n_{LC}(\alpha) = \frac{n_o n_e}{\sqrt{n_o^2 \sin^2(\alpha) + n_e^2 \cos^2(\alpha)}} \tag{1}$$

where n_o and n_e are the ordinary and extraordinary index respectively and α is the angle between the optic axis of the liquid crystal and the direction of propagation of the light beam in the 2D-PhC. In our configuration, being the polarisation state maintained, the eigenvalue equation for TM mode is solved putting $\varepsilon(r) = n^2_{LC}(\alpha)$ where $n_{LC}(\alpha)$ is given by Eq. (1), for the different orientation of liquid crystals director.

Applying an electric field, the dielectric constant of liquid crystals can vary from $\varepsilon_b = 2.25$, corresponding to initial position of director, to $\varepsilon_b = 2.89$ ($\Delta n_{lc} = 0.2$) corresponding to the final position of director (parallel to the rods). Being the dielectric constant of the LC background into the defect lines changed, the band gap of two branches will be modified, too. In Figure 5, the band gap of left (green bars) and right (red bars) branch for several liquid crystal orientations are reported. Of course, the frequencies range propagating into the left and right branches, being the complementary with respect to the band gap, are changed, too. Moreover, as you can see from Figure 5, the switching frequency experiences a significant shift.

Considering the following parameters: $a = 430$ nm, the lattice constant; R = 100 nm, the radius of 2D PhC; $r_1 = 70$ nm, the pillar radius

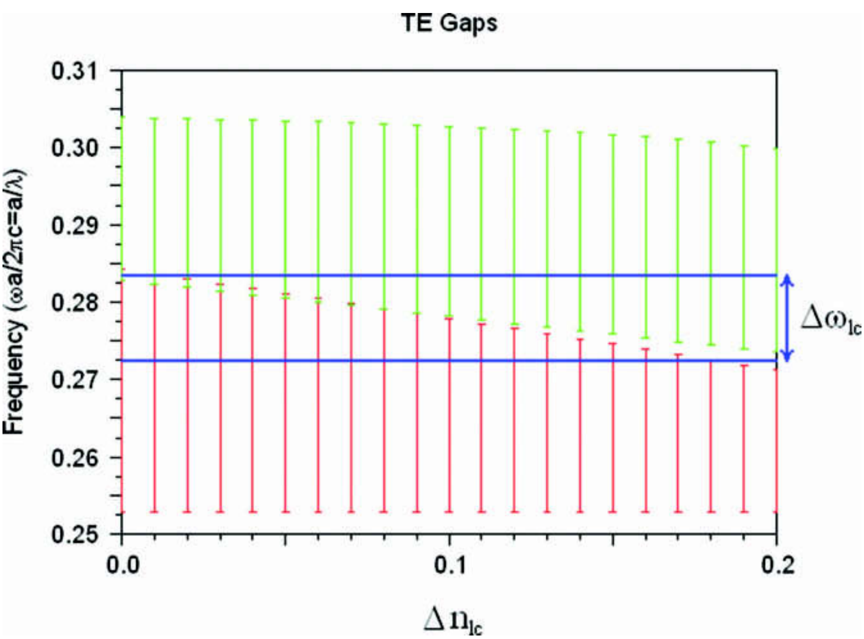

FIGURE 5 Gap of the left (green bars) and right (red bars) branch versus the difference between the reoriented LC refractive index with respect to the LC background refractive index. The maximum shift $\Delta\omega_{lc} = (0.0110) \times 2\pi c/a$ corresponding $\Delta\lambda_{lc} = 61$ nm is also indicated.

in the left waveguide; $r_2 = 125\,\mathrm{nm}$, the pillar radius in the right waveguide; $\Delta n_{lc} = 0.1$ the refractive index difference between the liquid crystals background and the reoriented liquid crystal in the defect lines of T junction; we obtain that the initial switching frequency is fixed at $\lambda = 1.55\,\mu\mathrm{m}$. Applying an electric field, a variation from $\Delta n_{lc} = 0$ up to $\Delta n_{lc} = 0.2$ can be obtained; therefore, the switching frequency can shift both at lower and higher frequencies. As you can see from Figure 5, a maximum shift $\Delta\omega_{lc} = (0.0110) \times 2\pi c/a$ corresponding to $\Delta\lambda_{lc} = 61\,\mathrm{nm}$ can be achieved.

CONCLUSION

We have numerically investigated the operation and the wavelength tunability of a T-shaped waveguide diplexer based on a 2D silicon photonic crystal. The first advantage of proposed device is that wavelength crosstalk between two outputs of T-junction is eliminated.

Moreover, changing the refractive index of the LC's by electro-optic effect, an active control of the splitting wavelengths range can be obtained. The switching wavelength can be tuned in a range of 61 nm. This means that the working wavelength range of our device covers all the C band (1525–1565) and also a small part of L band.

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