# A Liquid Crystal Tunable Wavelength-Interleaved Isolator With Flat Spectral Response

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***Abstract*—A liquid crystal tunable bidirectional isolator is proposed. A wave plate is employed to realize a wavelength interleaving function. If it works as a full wave plate, the corresponding light only may pass along a specific direction while the opposite way is isolated. However, for wavelengths that the light experiences a half wave plate, the isolator's passing direction is reversed. A liquid crystal cell is utilized to tune the isolator so that both the isolated wavelength and direction could be reconfigured. A 100-GHz channel-interleaved tunable bidirectional isolator is demonstrated with $\sim$30 dB isolation in both directions. The spectral response at ITU grids are further flattened by using a wave plate stacking technique.**

***Index Terms*—Interleaver, liquid crystal, optical isolator, wave plates.**

## I. Introduction

ISOLATOR is widely used in laser, optical communication and optical processing systems [1]. It is a key element in protecting the light source and other optical equipments from being affected by the back reflected light. Bulk isolator and waveguide isolator are two major types. The former one has the advantages of easy fabrication, low cost, commercially available [2]–[4] while the waveguide type is more attractive in integration optics combined with Mach–Zehnder inteference [5]–[7] or surface plasmon excitation [8]. However, all these isolators are normally fixed allowing the light at the designed center wavelength propagating unidirectionally. On the other hand, the fast-growing Dense Wavelength Division Mulplexing (DWDM) reconfigurable optical network may need some more agile devices, [9] with adjustable spectral responses.

As an effective low-voltage electro-optic tuning approach, liquid crystal (LC) has been successfully used in fiber-optic devices, including wavelength blocker, variable attenuator, wavelength filter and Fourier spectrum analyzer [9]–[12]. However, to the best of our knowledge, there is rarely report on *LC* tuned isolators. It would be interesting to see if *LC* could be used for isolator applications.

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In this paper, a modified design of magneto-optical (MO) isolator is proposed. A wave plate is inserted between the polarizer and the MO Faraday rotator. The isolator thus shows wavelength dependency. For example, the odd ITU channels may only propagate forward while the opposite route is isolated. On the contrary, the isolated direction of the even channels is reversed. Based on this design, a 200 GHz channel spaced and 100 GHz wavelength interleaved isolator is experimentally demonstrated. A *LC* cell is used and works together with the fixed wave plate. As a consequence, spectral response of the isolator is tunable. The isolation direction even could be reversed at a certain driving voltage. A reconfigurable isolator thus is obtained.

## II. Optical Design

The schematic diagram of a tunable bidirectional isolator is depicted in Fig. 1. A pair of polarizers with 45° angular separation are placed at the input and output ports. A $YVO_4$ crystal, a *LC* cell with homogeneous alignment and a 45° MO Faraday rotator are assembled sequentially between the two polarizers. The crystal's optical axis coincides with the *LC* cell's rubbing direction so that they form a tunable wave plate combo.

The corresponding phase retardation of the incident beam in this wave plate combo is $\Gamma = 2\pi \cdot [\Delta n_1 L_1 + \Delta n_2(E) L_2]/\lambda$, where $\lambda$ is the light's wavelength, $\Delta n_1$ and $\Delta n_2(E)$ are the birefringence of the $YVO_4$ crystal wave plate and the *LC* cell, respectively. E is the applied field. $L_1$ and $L_2$ represent the crystal's and *LC* cell's thickness, respectively. From this equation, we can see that for a certain wave plate combo, it could perform as a full wave plate for some wavelengths and as a half wave plate for some other wavelengths. It provides wavelength dependence and helps to achieve the function of wavelength interleaved isolator.

As the crystal's thickness is normally around several millimeters while typical *LC* cell gap is in micrometer range, the total birefringence is mainly contributed by the crystal, but the *LC* cell can further tune the total phase retardation precisely. The initial retardation value is determined by the crystal's thickness and the preset *LC* bias voltage. Therefore, by designing the wave plate's thickness as well as adjusting the *LC* cell's bias voltage, we can control the combo to be a full wave plate or a half wave plate of the wavelengths we want to handle.

Just like other typical two-beam interferometers, the setup shown in Fig. 1 also has a sinusoidal spectral response in frequency domain. The free spectral range is $\mathrm{FSR} = C/[\Delta n_1 L_1 + \Delta n_2(E) L_2]$, where C is the light velocity. Let's assume a 200 GHz FSR to determine a suitable initial phase retardation. Without loss of generality, if the crystal/LC combo forms a full wave plate for wavelength $\lambda_1$, it becomes a half wave plate for another wavelength $\lambda_2$ as long

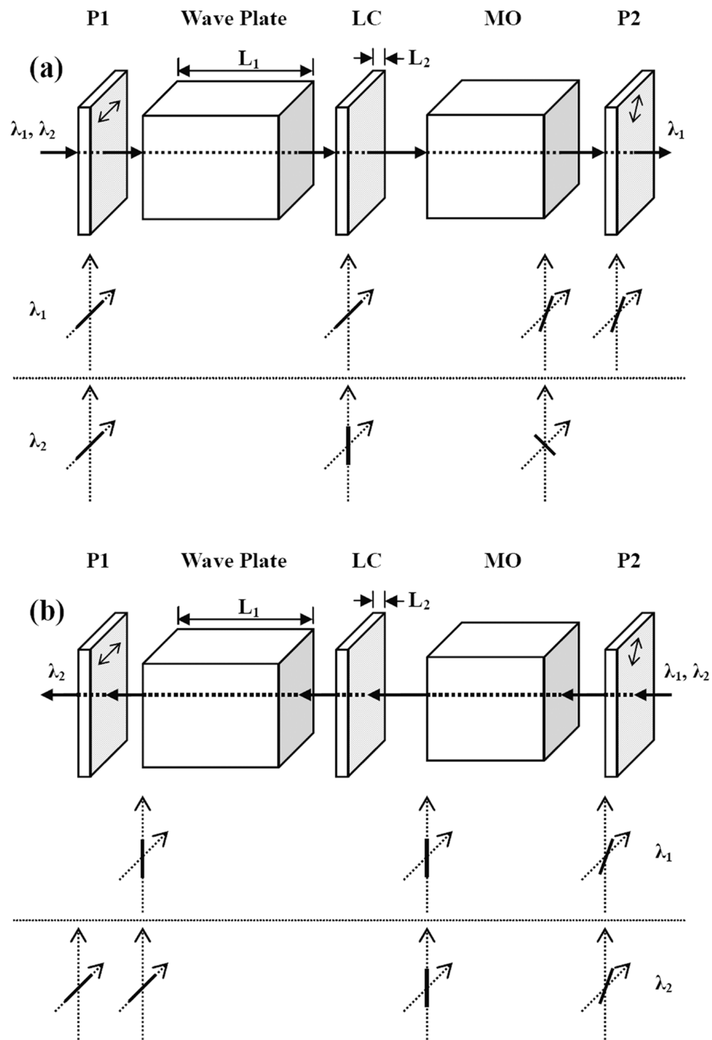


Fig. 1. Schematic diagram of a LC-based tunable bidirectional isolator and the evolution of the polarization state in forward direction (a) and backward direction (b).

as the frequency difference from $\lambda_1$ is 100 GHz, 300 GHz, 500 GHz ….

The evolution of the light's polarization state is shown in Fig. 1. The $YVO_4$/LC wave plate combo is designed and set as a full wave plate for $\lambda_1$ and a half wave plate for $\lambda_2$. In Fig. 1(a), lights containing both $\lambda_1$ and $\lambda_2$ components travel from left to right, passing the polarizer (P1) first. Hence, $\lambda_1$ and $\lambda_2$ lights are linearly polarized along 0° orientation, parallel to P1. When lights travel through the wave plate, polarization states of $\lambda_1$ and $\lambda_2$ become different. As a full wave plate for $\lambda_1$, the polarization is still at 0° for $\lambda_1$. Meanwhile, the polarization of $\lambda_2$ changes to be 90° as the wave plate is a half wave plate for $\lambda_2$. The 45° MO Faraday rotator rotates both the $\lambda_1$ and $\lambda_2$ lights by 45°, making the polarization of $\lambda_1$ and $\lambda_2$ to be 45° and 135° oriented, respectively. When the lights arrive in the right polarizer (P2) with it optical axis set at 45°, light with wavelength $\lambda_1$ could pass through the polarizer. But for light with wavelength $\lambda_2$, its polarization state is orthogonal to the P2, leading to be an isolated state.

Fig. 1(b) shows the evolution of polarization state when lights travel from right to left. In this situation, lights travel through the right polarizer (P2) first, making the polarization directions of both $\lambda_1$ and $\lambda_2$ to be 45°. The MO Faraday rotator then further rotates the polarization directions of both $\lambda_1$ and $\lambda_2$ to be 90°. As a half wave plate for light with wavelength $\lambda_2$, the wave plate combo tunes the polarization direction of $\lambda_2$ to be 0°, which coincides with the direction of polarizer(P1). Therefore, light with wavelength $\lambda_2$ could pass through in the backward direction. However, for light with wavelength $\lambda_1$, its polarization direction is orthogonal to the polarizer (P1) after the light passed through the $YVO_4$ wave plate, so that it is blocked finally.

In a word, light with wavelength $\lambda_1$ may passe through the isolator in forward direction but is blocked in backward direction. Meanwhile, light with wavelength $\lambda_2$ passes through the isolator in backward direction but is blocked in forward direction. A wavelength interleaved bidirectional isolator thus could be obtained.

## III. Experimental Results and Discussions

To verify the design of our tunable isolator, a 7.36-mm long $YVO_4$ crystal with birefringence of 0.204 at 1550 nm is selected. A homogeneously aligned *LC* cell is used to tune the phase retardation. The cell gap is 8 $\mu$m and filled with Merck MLC6647 LC, which has the room temperature birefringence of 0.123 at 1550 nm. The crystal's optical axis and *LC* cell's rubbing direction are both 45°-orientated. The garnet is a commercial product that is specified to rotate the polarization state of 1550 nm light by 45°. Light from an ASE source is collimated into our isolator and finally coupled into another identical collimator. A YOKOGAWA AQ6370 optical spectrum analyzer (OSA) monitors the output spectra. Fig. 2(a) and Fig. 2(b) show a 5 THz-wide measurement spectra in forward and backward directions, respectively, covering the whole telecomm C-band. No voltage is applied to the *LC* cell at this time. It is obviously that the spectra have 200 GHz FSR, but the passing and isolated channels are 100 GHz interleaved, Take the position pointed by the arrow as an example, the channel centered at 193.5 THz is a passing channel along forward direction while it is an isolated channel along the backward direction, agreeing well with our expectations. The lowest insertion losses (IL) for the forward and backward directions are $-0.32$ dB and $-0.25$ dB, respectively, meeting the commercial requirements. The isolation reaches around 30 dB in both directions, which is also very nice.

Theoretically, the MO Faraday rotator's polarization rotation angle is inversely proportional to wavelength. That is $\mathrm{g} = \mathrm{C}/\lambda$, where g is the rotation angle, C is the Verdet constant of the Faraday rotator, $\lambda$ is the light's wavelength. In our design, we choose a Faraday rotator that could rotate the 1550 nm light's polarization by $\pi/4$. However, for other wavelengths in the telecom band, the polarization rotation angle is not exactly at $\pi/4$ any more, which results a higher IL in passing state and weaker isolation (ISO) in the isolated state. Assuming the working wavelength is $\lambda = \lambda_0 + \Delta\lambda$, where $\lambda_0$ is 1550 nm and $\Delta\lambda$ is the wavelength offset, the polarization rotation angle could be expressed by $\mathrm{g} = \mathrm{g}_0(1 - \Delta\lambda/\lambda_0)$, where $\mathrm{g}_0 = \pi/4$ is the ideal polarization rotation angle at $\lambda_0$. In this case, IL and ISO are expressed as

$$\begin{aligned} \mathrm{IL} &= -10\log\left\{\cos^2\left[\frac{\pi}{4} - g_0\left(1 - \frac{\Delta\lambda}{\lambda_0}\right)\right]\right\} \\ \mathrm{ISO} &= -10\log\left\{\cos^2\left[\frac{\pi}{4} + g_0\left(1 - \frac{\Delta\lambda}{\lambda_0}\right)\right]\right\} \end{aligned} \quad (1)$$

From the above equations, $\mathrm{ISO} = 0$ and $\mathrm{IL} = 1$ at $\lambda_0$, meaning all lights are blocked in the isolated stated while there is no extra attenuation other than the propagation loss in the passing state. For $\Delta\lambda = \pm 20$ nm, the wavelength is 1530 nm or 1570 nm at the edge of telecom C-band. $\mathrm{IL} \approx 1$ and $\mathrm{ISO} \approx -39.88$ dB are obtained, meaning the wavelength interleaved isolator could work in the whole C-band in theory. However, the measured isolation is only around $-30$ dB, there should be still some room for improvement, if the wave plate uniformity, Faraday rotator and polarizers' quality could be further improved.

Moreover, the spectral response of our bidirectional isolator could be tuned by the *LC* cell. The total phase retardation is finely adjusted by applying different voltages. A full wave plate of $\lambda_1$ even may be tuned to be a half wave plate as long as an adequate voltage is applied. In this case, the original forward-passing and backward-isolated channels change to forward-isolated and backward-passing channels. The isolator is thus reconfigured. Fig. 3 shows the results at different driving

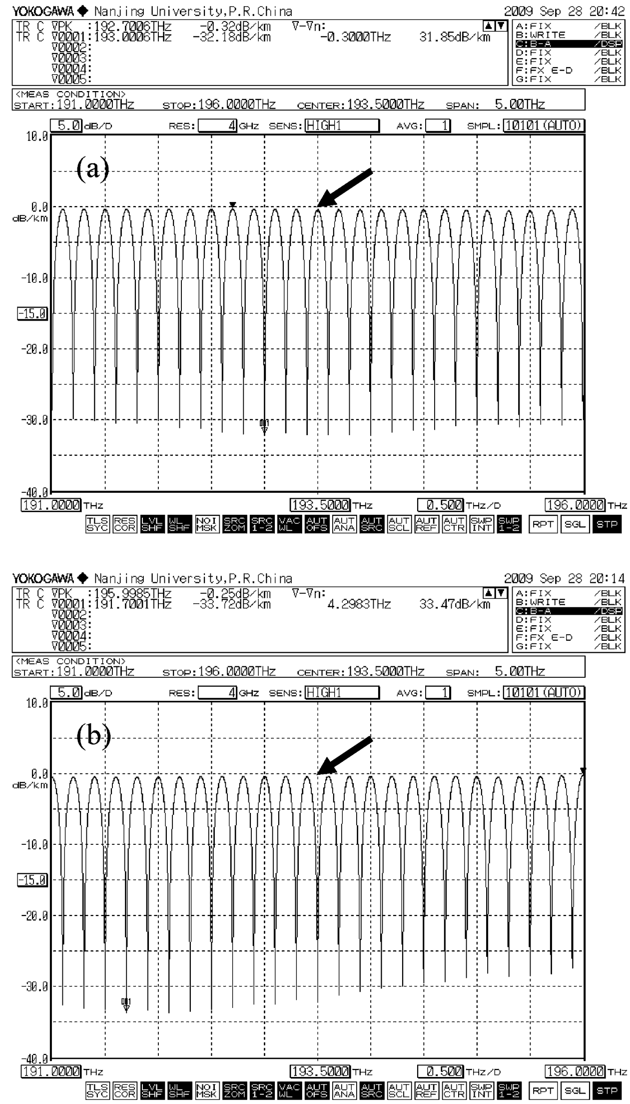


Fig. 2. The 5 THz-spectra of an bidirectional isolator in forward (a) and backward (b) directions.

voltages for forward propagated lights. The spectral range is shrunk to 1 THz for a better view. When there is no voltage is applied, the passing channels are centered at 193.1 THz, 193.3 THz, 193.5 THz, 193.7 THz and 193.9 THz, respectively. Channels with 100 GHz offset are isolated. When a 1 $\mathrm{V_{rms}}$ voltage is applied, there is no spectrum change. Only when a voltage over 1.5 $\mathrm{V_{rms}}$ is applied, an evident blue-shift of the spectrum happens. 1.5 $\mathrm{V_{rms}}$ is the corresponding threshold voltage. When the voltage is higher than 3.5 $\mathrm{V_{rms}}$, the spectrum is difficult to shift further more, thus the 3.5 $\mathrm{V_{rms}}$ could be viewed as a saturation voltage. From Fig. 3, there is a 100 GHz blue shift at 3.6–4 $\mathrm{V_{rms}}$ driving voltages. The original passing channels and isolated channels are swapped. The isolation direction of this isolator thus is reversed. The switching times between 0–4 $\mathrm{V_{rms}}$ states is measured ~40 ms. Although only the forwarded light spectra are recorded in Fig. 3, the backward lights experience the same spectral shift and channel-swap.

The channels bandwidth is also an important feature of a DWDM fiber-optic component. The 1 dB bandwidths of

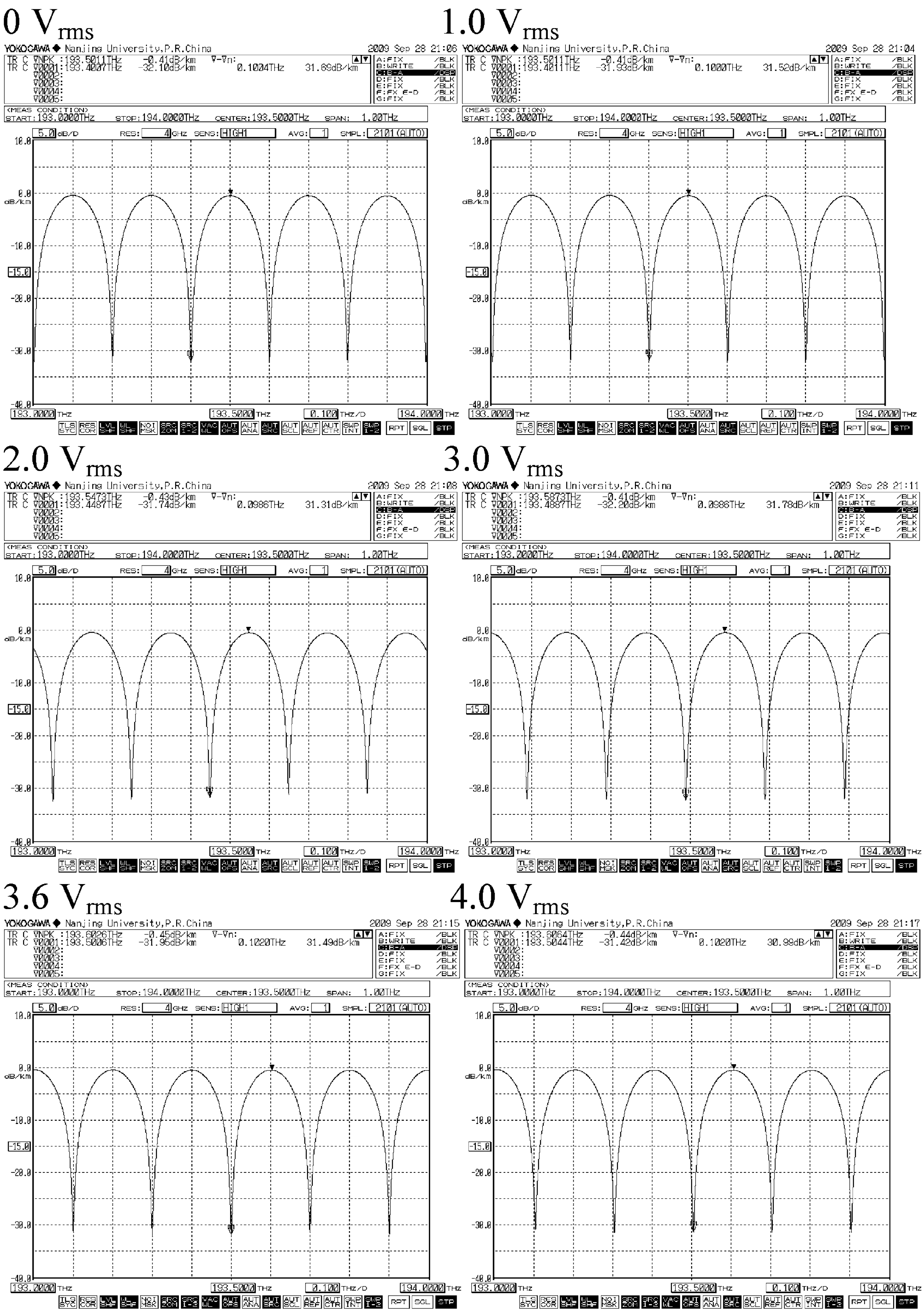


Fig. 3. The change of the spectra with different driving voltages applied on the *LC* cell.

the passing channels are ∼58.6 GHz, reading from Fig. 3. Because our isolator is basically a two-beam interferometer with sinusoidal spectral response, multi-beam interference should be adopted if we would adjust the spectral shape with wider bandwidth. To involve more interfered beams, a wave plate stack approach could be used [13]. Extra wave plates

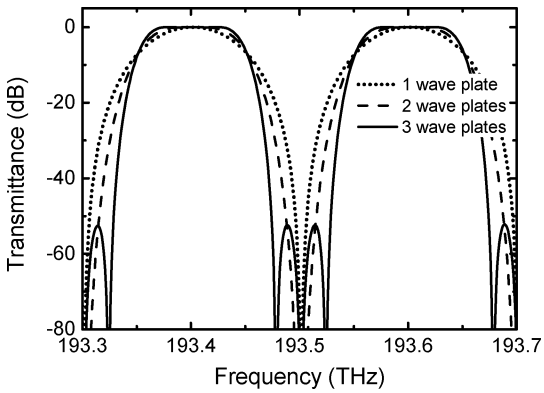


Fig. 4. Simulated spectral responses showing wider bandwidth with one, two and three wave plates inside an isolator.

with suitable thickness and orientation may be inserted in the isolator between the original crystal wave plate and the *LC* cell. In this case, when light enters the first wave plate, it is separated into two rays polarized along the wave plate's fast and slow axes, respectively. Their phase retardation is $\Gamma$ that determines the FSR. When lights enter the second wave plate with different orientation, four-beam interference could be obtained if the wave plates' thicknesses are different [13]. More wave plates result in more beams involved. Normally the added new wave plates have the same or doubled thickness as the first one to keep the original FSR. S. E. Harris *et al.* proposed an optical network synthesis technique that may obtain arbitrary transfer spectra with a serial of cascading wave plates [13]. For our isolator, Harris's approach may be employed, but we may also use a simplified way if there are only 2–3 wave plates. To obtain a wide bandwidth, we set the first wave plate's optical axis at 45° then adjust the second wave plate's orientation and monitor the spectral change until the widest bandwidth emerges. Whereafter, the third waveplate's orientation could be further adjusted for better results. Although this approach is too straightforward and may miss the best solution, it works well for our wavelength interleaved isolator.

Fig. 4 shows the simulation results of 200 GHz FSR isolators with one, two and three wave plates, where the second and third wave plates have doubled length. From the figure, when the second wave plate oriented at $-16°$, the bandwidth is greatly expanded. After the third wave plate at 9° is inserted, a wider and flatter spectrum is obtained. To demonstrate the predicted effect, Fig. 5 shows the experimental results when two wave plates are used. Flat-top spectra are achieved for both forward and backward propagated lights.

Although the wavelength interleaved isolator shows some unique properties, it is polarization dependant. However, most telecom devices should be polarization insensitive. To improve the performance, a modified design is proposed as shown in Fig. 6. A pair of beam displacer (BD)/half wave plate (HWP) combo is utilized instead of the two 45° separated polarizers in Fig. 1. When a light with arbitrary polarization passes through the first beam displacer (BD), it is split into two orthogonally polarized beams, named the ordinary ray and the extraordinary ray. A HWP is bonded with the beam displacer, rotating the

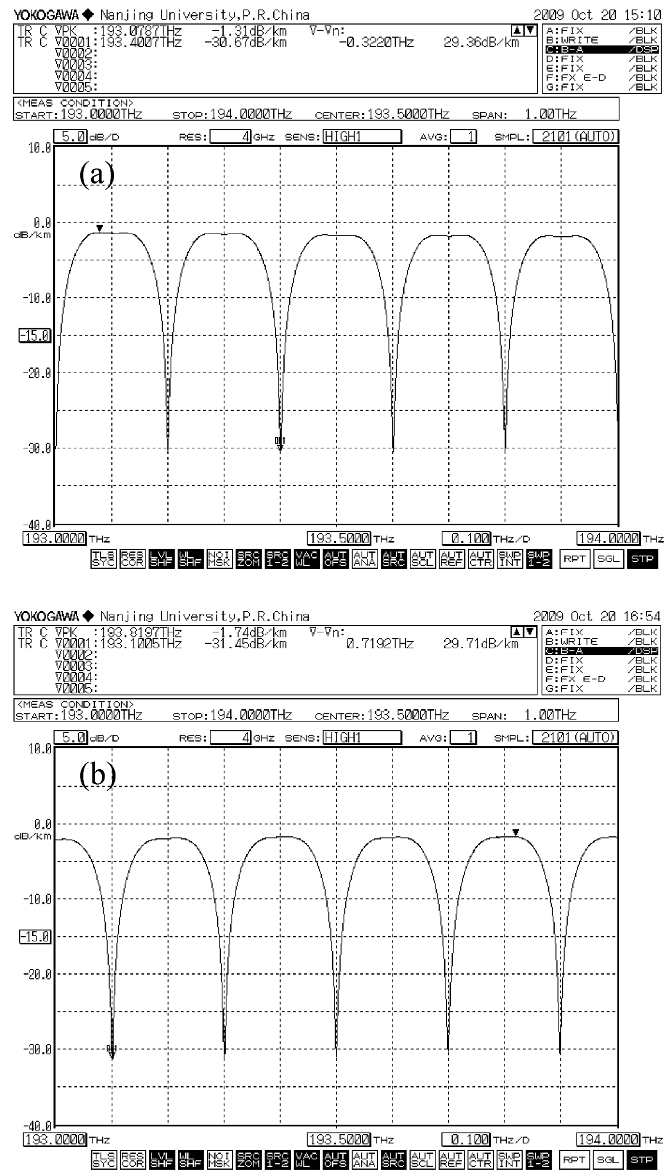


Fig. 5. 1 THz-spectra of a bidirectional isolator containing two $YVO_4$ plates. (a) and (b) are for the forward and backward directions, respectively.

extraordinary ray's polarization by 90°. Thus, BD/HWP just acts as the first polarizer P1 in Fig. 1. After the lights with arbitrary polarization pass through the isolator core, a 22.5° oriented HWP further twist the polarization by 45°. At last, another identical BD/HWP combo collects the upper and lower beams. When $\lambda_1$ light propagates forward from left to right, the beams could pass through the second BD and recombined together with low loss. This is just the passing state. Detailed polarization evolution is also displayed in Fig. 6(a). However, when $\lambda_2$ light enters the isolator, the final polarization states of the upper and lower beams change 90°, so that they may not recombine, corresponding to an isolated state as shown in Fig. 6(b). When lights propagate backward from right to left, the required passing or isolated stated also may be obtained for arbitrary polarization states. A polarization insensitive wavelength interleaved isolator thus could be realized.

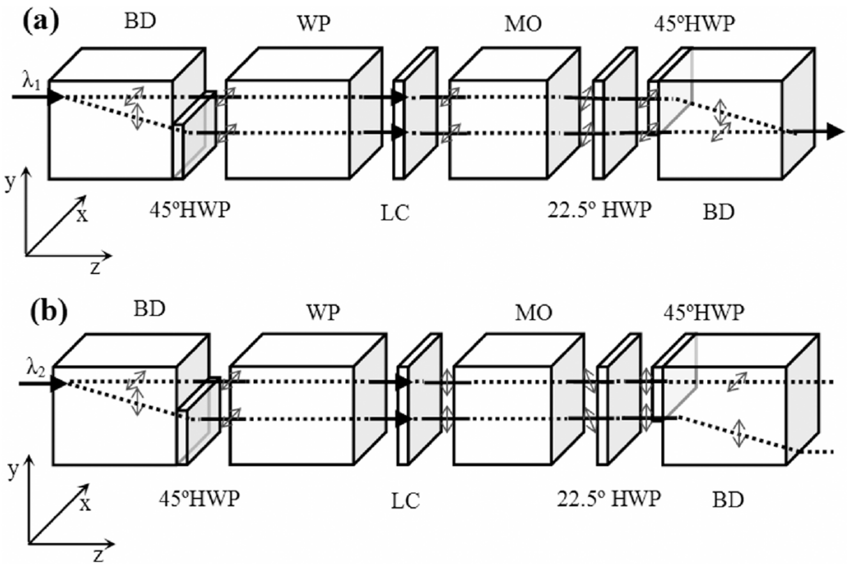


Fig. 6. Schematic diagram of a polarization insensitive isolator design showing (a) $\lambda_1$ light is passed and (b) $\lambda_2$ light is isolated from left to right.

## IV. Conclusion

A liquid crystal based tunable bidirectional isolator is proposed and demonstrated. A birefringent crystal or crystal stack is used so that wavelength interleaved spectra are obtained with 200 GHz channel spacing. The center wavelengths match the ITU Grids very well. The center frequencies of the passing and isolated channels can be tuned by liquid crystal with a low voltage. Even the isolation direction could be swapped at 3.6 $V_{\rm rms}$ driving voltage. A maximum isolation over 30 dB is measured in both directions. $\sim$100 GHz 1 dB bandwidth has been observed by using a crystal-stack technique. We believe our device is very useful in future agile and reconfigurable long haul or metro DWDM optical networks.

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