Dispersion Enhancement and Linearization in a Dynamic DWDM Channel Blocker

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***Abstract*—A dynamic dense-wavelength-division-multiplexing (DWDM) channel blocker and equalizer is developed based on liquid crystal (LC) and dispersion control technology. A multipixel *LC* array is adopted to regulate the power level of each DWDM channel, while a reflective grating diffracts the input signals spatially to corresponding *LC* pixels. A dispersion control unit is proposed and employed to enhance the dispersion and compensate the intrinsic nonlinear dispersion of the grating. Therefore, all *LC* pixels could handle corresponding lights centered at the International Telecommunications Union Grids. A 40-channel, 100-GHz channel-spacing dynamic wavelength blocker/equalizer is thus demonstrated with −5 dB insertion loss and over 40 dB extinction ratio. The maximum center frequency shift of all 40 channels is ∼±2 GHz, which means our dispersion control technology works very well for grating-based DWDM devices.**

***Index Terms*—Diffraction gratings, fiber optics components, liquid crystal (LC) devices, multiplexing.**

I. Introduction

RECONFIGURABLE optical add/drop multiplexer (ROADM) is a key enabler for dynamic optical layer reconfiguration in a dense-wavelength-division-multiplexing (DWDM) network. Individual channels (wavelengths) of optical traffic thus are routed in a timely manner. Most of the worldwide key system providers are going to deploy ROADM-based optical networks. As an effective solution of ROADM, dynamic wavelength blocker/equalizer (DWBE) has attracted attentions from both industry community and research institutes [1]. The DWBE controls individual channels to be passed, blocked, or equalized dynamically so that it may work together with light couplers, optical Mux/Demux and channel monitor to realize a ROADM function. Up to date, a number of technical approaches for DWBE have been explored, including planar light circuit [2], [3], fiber Bragg gratings [4]–[6], and free-space designs [7]–[11]. Among them, free-space configurations have the advantages of easy upgradeability, cost-effectiveness and large channel-handling capability. Normally, a bulk diffraction grating is employed to separate lights according to their wavelengths then a power regulation unit further controls their powers. As DWBE requires multichannel light handling capability, microelectromechanical system (MEMS) [7]–[9] and liquid crystal (LC) [10], [11] are two natural choices for light power regulation. This is quite similar to the case in projection displays, where Texas Instruments' Digital Micromirror Device is competing with the *LC* on silicon technology. The key advantages of using *LC* instead of MEMS include no moving parts, low energy consumption, and proven reliability [12]. In addition to DWBE, wavelength selective switch (WSS) is another ROADM solution. Actually, the DWBE could be viewed as a 1-D version of WSS. Their key fundamental functions such as wavelength dispersion and light power regulation are similar, thus the technologies developed for DWBE could be easily transferred to a WSS so that the development cost could be reduced.

In this paper, a dispersion enhancement and linearization technology is proposed and applied in the design and development of a compact 40-channel, 100-GHz channel-spacing grating-based DWBE. Zemax optical simulation software is used to determine the optimized parameters of each element. Both the theoretical simulation and experimental results demonstrate that the grating's intrinsic nonlinear dispersion is eliminated, while the spatial dispersion is 1.53 times enhanced. The final center frequency shift is measured to be only ±2 GHz. With the help of a 40-pixel *LC* array, the maximum dynamic range over 40 dB is achieved. Insertion loss (IL), polarization-dependant loss (PDL), and bandwidth (BW) measurements shows that the overall performance of our DWBE meets the practical ROADM applications.

II. Optical Design and Dispersion Control

To design a DWBE in free-space configuration, a wavelength dispersive element is the fundamental component by which different channels could be directed to different position according to their wavelengths. Then either an *LC* or MEMS arrayed modulator could be employed for power regulation individually at each channel. As a mature wavelength dispersive technology, bulk grating has been widely used in various spectrometers, which could also be applied in DWBE. However, DWDM has very close channel spacing, e.g., 50, 100 GHz. It is not easy to

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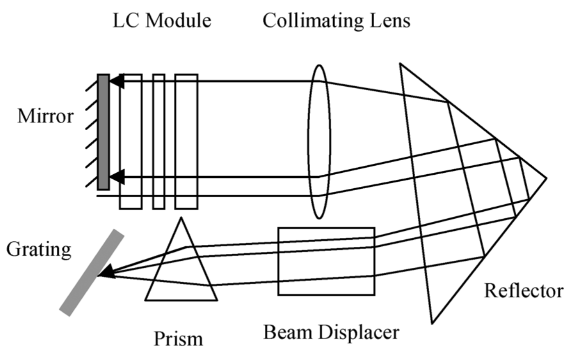

Fig. 1. Schematic diagram of an LC-based DWBE.

design a compact system with such a high dispersion. In addition, the angular dispersion of a bulk grating is intrinsically nonlinear in optical frequency domain, which means the diffracted channels cannot be equally spaced at the *LC* or MEMS plane. Therefore, the center frequency corresponding to each *LC* or MEMS pixel will have an offset to International Telecommunications Union (ITU) Grids. As a consequence, a high-dispersion and linearly distributed dispersive module is very critical for both *LC* and MEMS-based DWBE designs.

The power regulation module (e.g., *LC* or MEMS modulator) is another important component of a DWBE. It dominates the spectral characteristics. The spectral response with high extinction ratio and low interchannel leakage is necessary to avoid the interference between the remainder of the blocked signal and the signal added to the same wavelength in ROADM.

Fig. 1 depicts the schematic diagram of an LC-based DWBE. A collimating lens is used to collimate the beam that comes out from a lensed fiber. A retroreflector placed behind the collimating lens folds the optical path. A beam displacer/half wave plate combo adjusts the output beam's polarization state to a certain direction. A reflective-type grating is used with Littrow mounting. The beams are angularly diffracted by the grating according to their wavelengths and then pass back through the *LC* array module that controls the individual channels to be passed, blocked, or equalized by applying different voltages. A mirror reflects the beams back, making the device more compact. In this case, the reflected lights pass through the *LC* module again, allowing a more effective modulation. Finally, the collimating lens collects the beams back to the original fiber.

Since the DWBE is designed to match the ITU frequency Grids, to ensure a linear dispersion is very desirable. However, for an ordinary diffraction grating, its angular dispersion in frequency domain could be deduced from the grating equation, which is

$$\frac{d\beta}{df} = \frac{-c}{f^2 \Lambda \cos\beta} \tag{1}$$

where β is the diffraction angle, f is the light frequency, Λ is the grating pitch, and c is the velocity of light. From (1), it is clear that the angular dispersion of the grating depends on the frequency of the incidence beam. When a lens with focal length F is employed, the angular dispersion is converted to spatial dispersion as

$$\frac{dL}{df} = \frac{d\beta F}{df} = \frac{-cF}{f^2 \Lambda \cos\beta} \tag{2}$$

which is still a complicated nonlinear function rather than a constant in ideal case. *dL* in this equation is the distance at the focal plane between two beams with *df* frequency spacing.

The desire of linear spatial spacing forces us to compensate the nonlinear dispersion of the grating. Here, we propose to use a prism for this purpose as it is also a widely used dispersive element. As shown in Fig. 1, a prism is inserted in front of the grating. The beams pass though the prism twice when they propagate toward and away from the grating. As a consequence, two major effects come out that affect the overall DWBE properties. The input beam containing a plurality of DWDM wavelength channels are deflected by the prism after leaving its back surface. The beam width thus changes consequently. As we know, a grating's resolution $\Delta f/f = 1/N$ is inverse proportional to the covered grating grooves. A wider beam results in higher resolution, which is very favorable. On the other hand, when the diffracted beams pass through the prism again, the angular dispersion is further changed as prism is also a dispersive element, which gives the opportunity to optimize the overall dispersion.

In our experiments, a 1200-line/mm grating is selected. The incidence angle for Littrow mounting is calculated to be 68.4° for 1550 nm light. In this case, a 1 mm width beam could cover 3260 grating grooves, so the resolution is 0.0003. When an $F =$ 60 mm collimating lens is used, the angular dispersion of the grating is converted to be spatial dispersion at the lens's focal plane. Fig. 2(a) shows the results. It is clear that two channels with 4 THz spacing are separated ~5.5 mm at the lens focal plane. From the curve's best fit result, its second-order polynomial coefficient is 0.015, which represents the nonlinear part of the grating's dispersion.

Just as we proposed, a prism inserted in the light path may affect both the resolution and dispersion. The prism's index, vertex angle and incidence angle are three parameters that influence the whole device's properties. With the help of a self-developed program and verified by Zemax optical design software, optimized prism parameters were obtained with higher resolution and improved dispersions. When a 30° BK7 prism is used with 57.3° incidence angle, the beam width at the grating surface enlarged 1.53 times, which means the resolution is also 1.53 times improved. As for dispersion, the measurement results are shown in Fig. 2(b). When the prism is employed, the dispersion is enhanced evidently. A 4 THz wide spectrum could be separated ~9.75 mm. Comparing to the state without prism, the dispersion is greatly enlarged. More attractively, the best fit second-order polynomial coefficient is only −5.65E-5, which is almost diminished. In this case, all adjacent channels with 100 GHz spacing are equally separated with 250 μm distance, which is a typical fiber array pitch value.

With the help of a well-designed prism, the center frequency shift of each channel thus could be confined within a

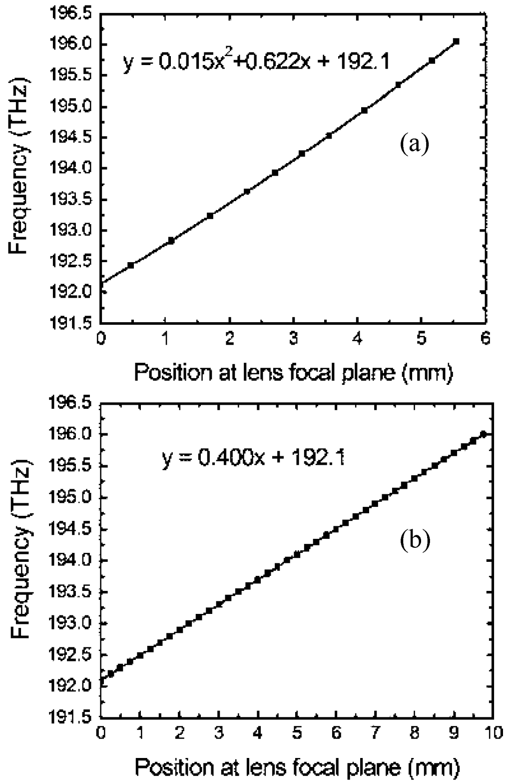

Fig. 2. Spatial dispersion curves of a 1200-lines/mm grating (a) before and (b) after a prism is employed.

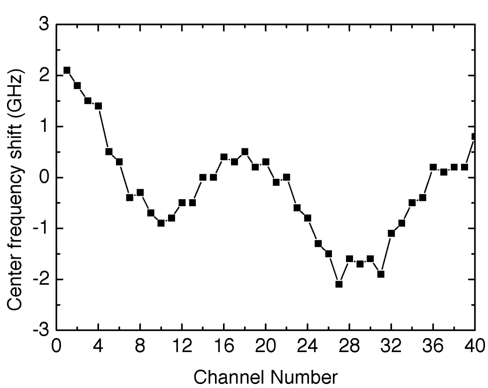

Fig. 3. Measured center frequency shift of a 4 THz wide spectrum.

very narrow range. From our experimental results, ± 2 GHz center frequency shift was achieved for a 40-channel, 100 GHz spacing DWBE, as shown in Fig. 3, which means our dispersion enhancement and linearization technology works very efficiently.

III. Design of Power Regulation Unit

A key specification of a DWBE is the adjacent channel crosstalk, which could severely affect the system performance. High crosstalk means too much leakage of signal into neighboring channels, which causes more bit errors. In addition to the crosstalk, bit errors also come from the interference between the remainder of the blocked signal and the signal added to the same wavelength in ROADM, a high extinction ratio and

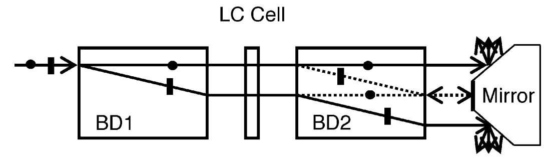

Fig. 4. Side view of the *LC* module for light power regulation.

low interchannel leakage are crucial for DWBE design. Hence, for LC-based DWBE design, a high-performance *LC* array with seamless concatenation of adjacent pixels for continuous filtering characters is required (i.e., *LC* cell and interpixel gaps). If the interpixel is too large, the light may leak through the interpixel gap when both channels are supposed to be blocked. To optimize the DWBE's driving voltage and provide appropriate predictions for the device's performance, we must thoroughly study the driving electrical field distributions, especially those within the interpixel gap of the *LC* cells, before any realistic design.

In our LC-based DWBE, the manipulation of the individual channels is implemented by an *LC* array in which individual cells are controlled by different driving voltages. The *LC* array is just a 1-D-multipixel twisted-nematic (TN) *LC* cell sandwiched between two parallel indium tin oxide (ITO) glass plates. One plate, with ITO fully coated, is used as the common electrode, while another plate is a patterned multipixel ITO plate. The rubbing axes are oriented with respect to the polarization axes of the incoming beams so as to rotate the polarization by 90° when the driving voltage between the two electrodes is zero. To illustrate the "ON" and "OFF" states, Fig. 4. depicts the side view of the combination of an *LC* module and a slit mirror. The *LC* module consists of an *LC* cell placed between two polarization beam displacers (BDs). The incidence beam with arbitrary polarization is split by the first BD into two orthogonally polarized components, named the ordinary ray (represented by the dots in the figure) and the extraordinary ray (represented by the bars in the figure). If a zero voltage is applied to the *LC* cell, the beam transferring in the DWBE could be passed. When two orthogonally polarized components pass through it, the *LC* rotates the polarization state by 90°; therefore, two components are recombined when they leave the second BD, which has the same length as the first one and hit normally to the slit mirror. The light paths within the second BD in the "ON" state are represented with the dash lines, as shown in Fig. 4. The mirror reflects the light back to its original path. On the other hand, if a high-enough driving voltage is applied to the *LC* cell, the TN LC's polarization rotation effect [13] is broken so that two orthogonally polarized components remain their original polarization states. No light hits the top area of the slit mirror. The lights are scattered away at the side walls of the mirror, which is the "OFF" state, as shown in Fig. 4 with solid lines. Adjusting the applied voltage, any attenuation state could be obtained.

IV. Device Packaging and Measurement Results

From our previous analysis, both the dispersion control and light power regulation functions are very critical for a DWBE, which are accomplished by grating/prism and *LC* module, respectively. However, other components are also important for a high-performance DWBE. For example, the collimating lens should be customer designed to control the aberration; the retroreflector and BDs should be slightly tilted to suppress the chromatic dispersion; all optical surfaces should be AR coated to lower the IL. In addition to the optical design, the tuning and packaging processes of the DWBE are even more difficult as the parts are very sensitive. For example, a $20'$ grating rotation may result in a 10 μm lateral offset at the *LC* array, which is unacceptable. After continuous efforts, we eventually developed the packaging techniques. A C-band 40-channel 100-GHz channel-spacing LC-based DWBE is successfully demonstrated in our laboratory. An Agilent 1200-line/mm holographic diffraction grating is used. A 30° BK7 prism is selected for dispersion enhancement and linearization as we discussed earlier. In this case, the 40-channels DWBE covers 4 THz spectrum range at C-band from 191.8 to 195.7 THz. The $<$2 GHz center frequency shift of each channel is achieved. As for the *LC* module, a self-developed nematic *LC* mixture with birefringence of 0.19 used. To make sure the *LC* cell works at high temperature up to 70 °C, the cell gap is designed at $\sim$9 μm, a little thicker than the requirement of the first-minimum Gooch–Tarry condition [13], which is $\sim$7.1 μm at 1550 nm. The cell gap is controlled by the spacer placed between two glass plates with ITO electrodes. Gap uniformity within $\pm$0.1 μm is required. The room temperature switching times between 10%–90% intensity is $\sim$6 and $\sim$90 ms for applying and withdrawing the electric field, respectively. To improve the speed, a homogeneously aligned *LC* cell could be used instead of a TN cell. There is even report of submillisecond response in dual-frequency addressed *LC* cells [12]. However, as TN *LC* is more stable and insensitive to cell gap variation, we still select it for our experiments. Because our *LC* array is mainly developed in the laboratory rather than a commercial product, the IL and interpixel uniformity are very poor. For example, a commercial *LC* cell normally has the IL of $<$0.1 dB, while our LC's IL is around 0.45 dB. All these may affect the final performances of the DWBE.

In our optical design, the input port and output port share the same fiber, a circulator thus has to be used to realize the DWBE function. An amplified spontaneous emission source connects to the circulator to act as a wideband light source. An Ando AQ6317B optical spectrum analyzer monitors the output spectra at different driving voltages onto the *LC* array.

Fig. 5. shows the measurement spectrum of the DWBE, where all odd channels have no field applied while even channels are attenuated or blocked by applying different driving voltages. The minimum IL is measured to be -4.97 dB, excluding the loss due to the circulator. More than 40 dB extinction ratio is achieved, as shown in Fig. 5. The corresponding pixel's driving voltage is only 3.65 $V_{\rm rms}$. If the driving voltages are adjusted to 2.85, 2.55, and 2.20 $V_{\rm rms}$, $\sim$30, $\sim$20, and $\sim$10 dB attenuations are obtained, respectively. When the driving voltage is withdrawn to 0 V like the odd channels, the minimum IL of corresponding channel is obtained. From Fig. 5, the maximum

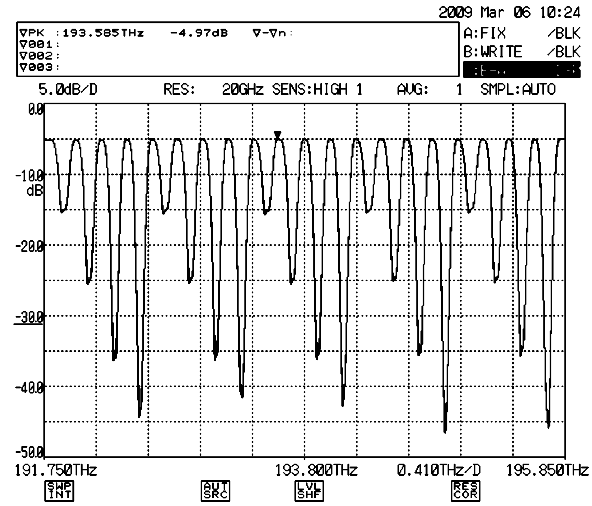

Fig. 5. Spectrum of a 100-GHz channel-spacing LC-based DWBE.

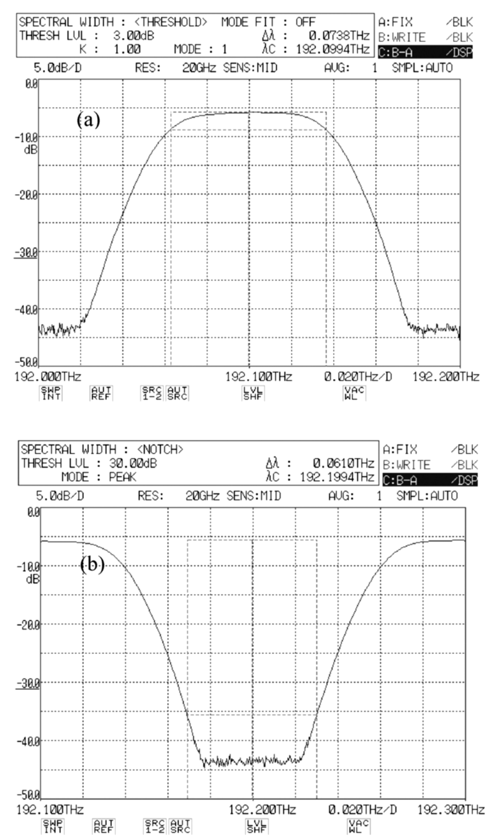

Fig. 6. Zoom-in view of (a) passed channel and (b) blocked channel spectra for a 100-GHz channel-spacing DWBE.

attenuations of some channels show some fluctuation. Some of them are lower than 40 dB. This should be due to the poor *LC* cell quality. Although 40 dB extinction ratio should be enough for ROADM applications, higher ratio also could be obtained by using the phase compensation technology [14].

Fig. 6(a) and (b) depicts a zoomed-in view of the Fig. 5 to illustrate the typical spectra of passed and blocked channels. The BW at -3 dB from the passband peak for the passband is 73.8 GHz, and the BW at -30 dB from adjacent passband peak for

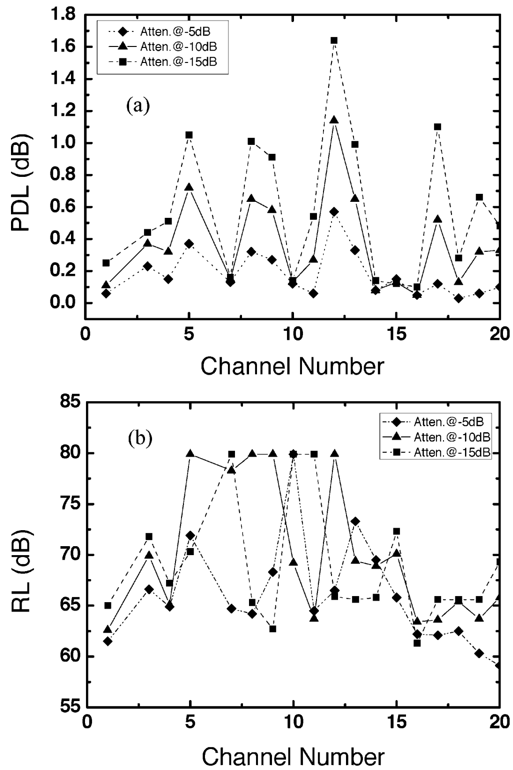

Fig. 7. Measured (a) PDL and (b) *RL* different attenuation states.

the blockband is 61.0 GHz, which is wide enough for DWDM applications.

Fig. 7(a) and (b) depicts the PDL and return loss (RL) of our DWBE. When the attenuations are at -5, -10, and -15 dB, the PDLs are less than 0.4, 0.7, and 1.1 dB, respectively, for most of the individual channels, but one channel performs rather poor. The PDL at attenuation states should be contributed by the *LC* array, which means its quality needs to be improved. We believe using a commercial product would solve this problem. The RLs of the individual channels are also measured, as shown in Fig. 7(b), all channels at arbitrary attenuation states are better than 60 dB, which have reached commercial product standard.

V. Conclusion

In this study, we proposed a dispersion enhancement and linearization technology for DWDM devices. With the help of a specially designed prism, the grating's dispersion could be 1.53 times enlarged. Meanwhile, its intrinsic nonlinear dispersion is canceled successfully. A 40-channel 100-GHz channel spacing LC-based DWBE has been designed and fabricated. The minimum IL is ~ -5 dB. The 3 dB-BW of the passband and the 30 dB-BW of the blockband can reach 73.8 and 61.0 GHz, respectively. The ± 2 GHz channel center frequency shift is experimentally demonstrated. An extinction ratio of $\sim$40 dB has been achieved. The PDLs are lower than 0.4, 0.7, and 1.1 dB, respectively, at -5, -10, and -15 dB attenuation, respectively. The RLs for all channels are lower than 60 dB. We believe the overall performances of our DWBE could satisfy the fast-growing ROADM applications.

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