

Demonstration of a bandwidth-tunable optical passband filter with tunable attenuation

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A bandwidth-tunable optical passband filter with tunable attenuation is proposed. The filter, composed of a transmission liquid crystal array and high-resolution diffraction grating, was successfully demonstrated based on the compact spatial light design. Experimental results showed that the bandwidth, wavelength, and attenuation could be tuned by controlling the voltage applied on the liquid crystal array. The insertion loss was less than 3 dB; the attenuation tuning range was from 0 to 15 dB. The bandwidth tuning range was from 50 to 5000 GHz, which covered the full C band. The filter can meet the technical requirements of colorless-directionless-contentionless-flexible reconfigurable optical add/drop multiplexer.

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To realize higher network elasticity, the architecture of an optical communication network is evolving to a mesh structure. As the core subsystem in an optical network, the reconfigurable optical add/drop multiplexer (ROADM) is developed to network architecture that is colorless-directionless-contentionless-flexible (CDCF)^[1-4]. The optical passband filter with tunable bandwidth and wavelength is one of the most important optical devices in CDCF ROADM. At present, the filter is implemented in several schemes, mainly including multiple microring resonators, Mach-Zehnder interferometers, reflective cholesteric liquid crystals (LCs), etc.^[5-13] However, the schemes mentioned above cannot meet the technical requirements of the CDCF ROADM structure because of their narrow tunable bandwidth, large insertion loss, and poor temperature performance.

In this Letter, an optical passband filter with tunable attenuation is proposed and successfully demonstrated. The filter is based on a transmission LC array and compact spatial light design. The bandwidth tuning range was from 50 to 5000 GHz, which can cover the full C band. The insertion loss was less than 3 dB; the attenuation tuning range was from 0 to 15 dB.

A schematic view of the proposed optical filter is shown in Fig. 1. The filter has one input fiber collimator and one output fiber collimator. Such a design ensures that the filter can be used for bidirectional transmission. The polarization conversion unit is composed of one birefringent crystal YVO₄ and two half-wave plates^[14]. The polarization conversion unit can convert the input light into linear polarization light. The prism pairs are used for beam shaping. The grating is used for wavelength spatial demuxing/muxing. In the horizontal plane, different wavelengths are collimated by a lens. In the vertical plane, the beam waist

is coupled to the LC chips by the lens, increasing the coupling efficiency. The LC module is composed of one polarizer, a transmission LC chips array, and one reflective mirror. The LC array is based on the working mode of the electronically controlled birefringence (ECB) effect. As shown in Fig. 2, when powered off, the ECB LC in this Letter acts like a half-wave retarder. If the linear polarization direction of input light shows 45° with the module direction of LC, the linear polarization direction will rotate by 90°. When powered on, the birefringence effect

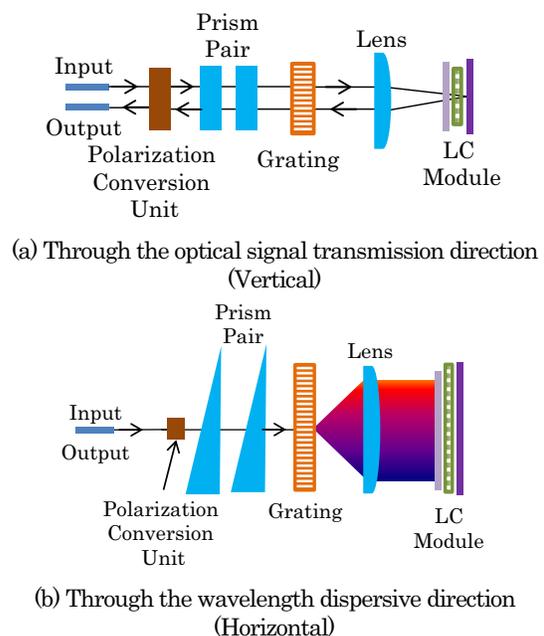


Fig. 1. Schematic diagram of the optical filter: (a) power off, (b) power on.

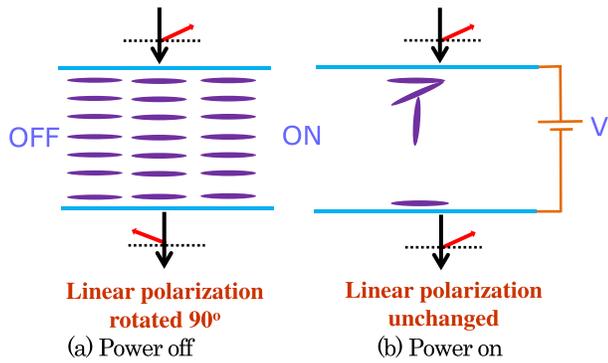


Fig. 2. Modulation principle diagram of the ECB effect (a) through the optical signal transmission direction (vertical) and (b) through the wavelength dispersive direction (horizontal).

will disappear, and the linear polarization direction will remain unchanged.

If adjusting the voltage applied on the ECB LC continuously, the polarization direction will rotate continuously. The output light intensity will vary according to the angle between the linear polarization direction and polarizer direction. In this Letter, the ECB LC array is adopted, which means that each wavelength compound can be attenuated or blocked by adjusting the voltage on each ECB cell independently. The width of the gap between adjacent ECB cells is less than $2\ \mu\text{m}$, as shown in Fig. 3, which is much smaller than the beam spot size on each ECB cell. This can make sure that the gap has no influences on the beam transmission, realizing flexible spectrum tuning.

Figure 4 shows the practical optical design in the software of Zemax. Two prism pairs are used for better beam expansion, which can enhance the bandwidth level. As shown in Fig. 5, the beam spot shape from the collimator is circular. After passing through the prism pairs, the beam spot changes to an elliptical shape. Different wavelengths are separated spatially with different angles by the reflection grating. Due to the uneven distribution of different wavelengths caused by the grating, the beam passes through prism pair 2 twice for reducing nonuniformity of dispersive angles. The lens in Fig. 1 is divided into two lenses, as shown in Fig. 4. Lens 1 is a spherical lens, working both in the optical signal transmission plane and wavelength dispersive plane. Lens 2 is a cylindrical lens,

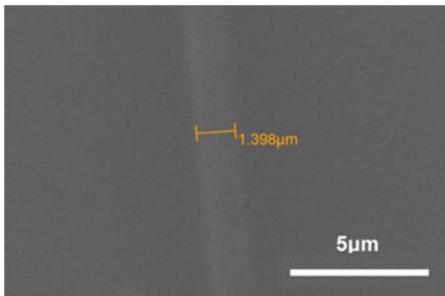


Fig. 3. SEM picture of the gap between adjacent ECB cells.

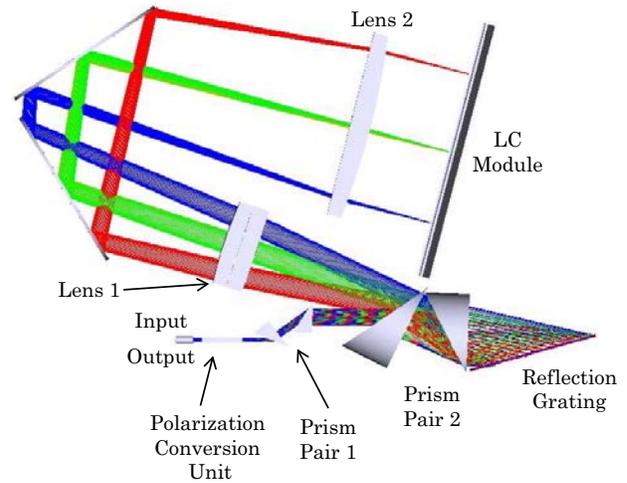


Fig. 4. Optical system design of the filter.



Fig. 5. Beam spot shape on the optical elements.

only working in the wavelength dispersive plane. Different wavelengths are coupled to their corresponding LC cells by lenses 1 and 2. Fold mirrors 1 and 2 are used for light path folding to realize a compact system design.

All parameters, including the positions, focal lengths, dimensions, etc., are theoretically calculated based on the Gauss beam coupling equation. The calculation can ensure the coupling efficiency after the Gauss beam passes through the entire optical system from the input fiber collimator to the output fiber collimator. All of the components and their functions are listed in Table 1.

A picture of the assembled optical filter is displayed in Fig. 6. The test system mainly includes one broadband laser source over the C band [amplified spontaneous emission (ASE) source], one optical spectrum analyzer (OSA), and one electronic controlling unit, as shown in Fig. 7.

As mentioned above, any wavelength could be attenuated or blocked by adjusting the voltage applied on the corresponding LC cell. This provides great flexibility when realizing a tunable optical filter. The experimental results shown in Fig. 8 indicate that the bandwidth can be expanded while keeping the center frequency unchanged. The bandwidth tuning range from 50 to 250 GHz is just an example. The maximum tuning range can be up to 5000 GHz. Furthermore, multiple wavelengths with different bandwidths can be sent to the output port together, as shown in Fig. 9. Figure 10 indicates that the filter can output an optical signal with fixed frequency granularity. All wavelengths over the entire C band can be tuned arbitrarily, as shown in Fig. 11. The insertion loss over the C band is less than 3 dB. Besides bandwidth and wavelength tunability, the optical filter can also provide a function of

Table 1. Components Used in the Filter

Component	Description
Input/output	Collimator array, for beam input and output.
Polarization conversion unit	Birefringent crystal and waveplate for the polarization conversion of input light to linearly polarized light.
Prism pair 1	Glass prism pair for beam expansion.
Prism pair 2	Glass prism pair for beam expansion and optimization of the wavelength dispersive angle.
Reflection grating	Reflection holographic grating for wavelength spatial demuxing/muxing.
Lens 1	Spherical lens for beam focusing of different wavelengths, working both in the optical signal transmission plane and wavelength dispersive plane.
Lens 2	Cylindrical lens working only in the wavelength dispersive plane.
Fold mirrors 1 and 2	Glass mirror for light path folding.
LC module	Polarizer, transmission liquid crystal chips array, and one reflective mirror for the wavelength blocking or attenuation.

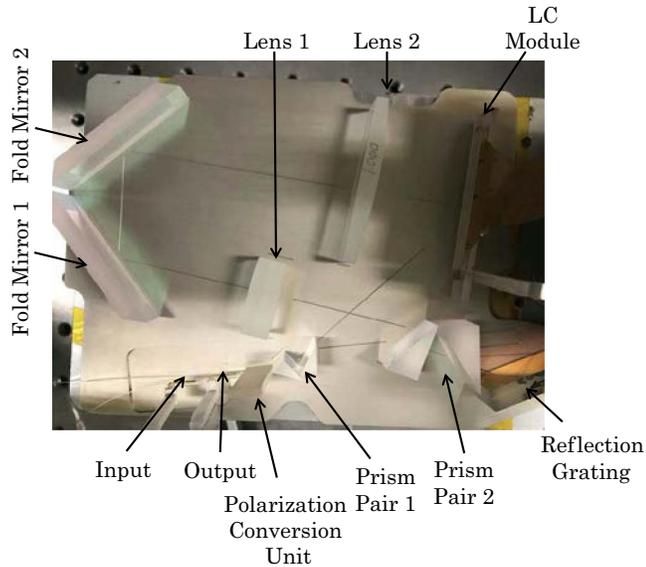


Fig. 6. Prototype picture of the assembled optical filter.

optical signal attenuation, as shown in Fig. 11. Any wavelength combination can be attenuated or blocked. The extinction ratio over the C band is greater than 45 dB.

The experimental results presented above show that the tunable optical filter has the merit of great flexibility. Any suitable wavelength tunable setting could be made

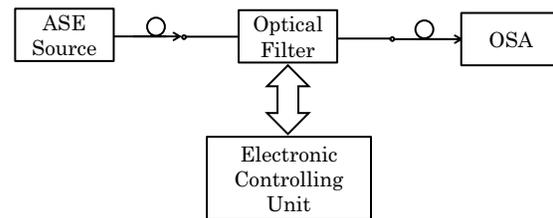


Fig. 7. Block diagram of the test system.

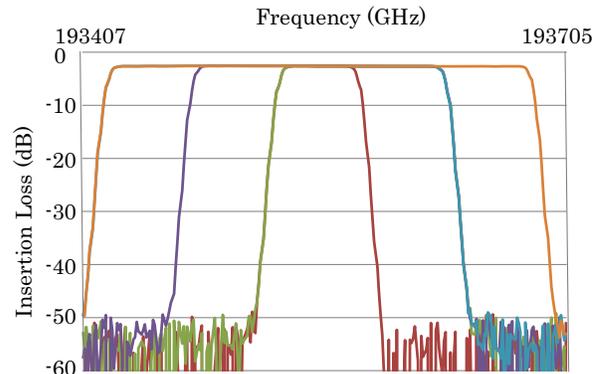


Fig. 8. Flexible bandwidth output from 50 to 250 GHz.

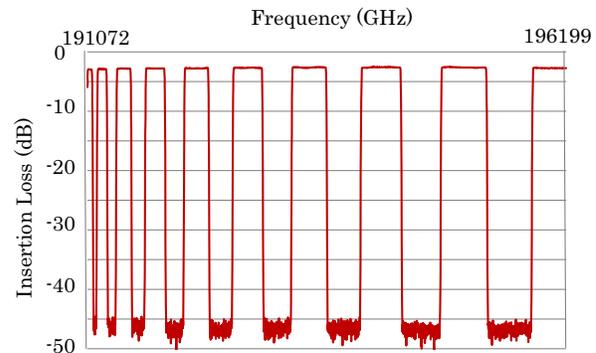


Fig. 9. Flexible bandwidth output (over C band).

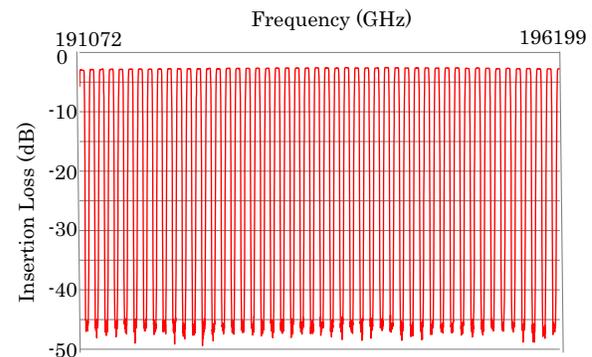


Fig. 10. Fixed bandwidth output over the C band (50 GHz granularity).

according to the real application, which meets the technical requirements of CDCF ROADM.

In conclusion, an optical pass band filter based on the transmission LC technology was proposed and

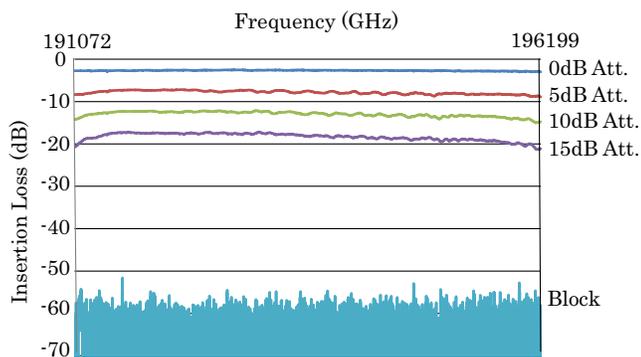


Fig. 11. All wavelength output, attenuation, and block (over the C band).

experimentally demonstrated. The insertion loss was less than 3 dB. The filter can output single wavelength with a tunable bandwidth or multiple wavelengths with different bandwidths. An optical signal through the filter can be attenuated or blocked. The attenuation tuning range was from 0 to 15 dB with resolution of 0.1 dB. The extinction ratio of blocking is greater than 45 dB. The experimental results indicated that the optical filter would have potential applications in the CDCF ROADM network.

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