A high performance tunable optical filter based on cascaded polarization interference filter

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A new kind of tunable optical filter is proposed for DWDM optical communication application. It is based on cascaded polarization interference filter (PIF). The period and bandpass width of each PIF are decided by its optical path difference between o-ray and e-ray (OPDOE). When their OPDOEs are proportionately designed, the tuning range and bandpass width depend on OPDOE in the first and the last PIF, respectively. The tuning range, bandpass width and crosstalk are independent each other. The crosstalk is related to the OPDOE ratios among PIFs and can be suppressed by designing the PIF's OPDOE. A set of OPDOE is suggested that are l_1, $2 \times l_1$, $2^2 \times l_1$, $2^3 \times l_1$, $2^4 \times l_1$, $\cdots$, $2^{N-4} \times l_1$, $15 \times 2^{N-7} \times l_1$, $10 \times 2^{N-6} \times l_1$ and $2^{N-2} \times l_1$ from the first to the last. This suggested OPDOEs can yield -50-dB crosstalk for any tuning range and bandpass width. The insert loss is less than 1 dB. As its loose alignment requirement, there is no limitation on cascaded PIF number. When 11 PIFs are cascaded, it can achieve 170-nm tuning range, -50-dB crosstalk, bandpass width applicable to 25-GHz channel spacing and 1 dB insert loss.

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A tunable optical filter is a key component in DWDM optical network which calls for wide tuning range, narrow bandpass width, low crosstalk, low insert loss and fast tuning speed. New type of tunable filter is being explored, such as long resonator micromachined tunable GaAs-AlAs Fabry-Perot filter[1], highly selective and widely tunable InP/air-gap micromachined Fabry-Perot filter[2], Lyot tunable liquid crystal filters[3], acoustooptic tunable filter[4−6], and widely tunable filter based on fiber Bragg grating[7]. However, as these filter's parameters: tuning range, bandpass width and crosstalk interrelate, it is a challenge for them to have high performance. Therefore, it is significant to make these parameters independent. Tunable filter using arrayed-waveguide grating is on this way[8].

In this paper, a new kind of tunable optical filter is introduced. It is based on cascaded polarization interference filter (PIF). Its parameters: tuning range, bandpass width and crosstalk, are independent each other. We can design and improve each parameter separately and achieve high performance. The tuning range and bandpass width are dominated by the optical path difference between the o-ray and the e-ray (OPDOE) in the first and last PIF, respectively. A set of OPDOE is suggested that can achieve -50-dB crosstalk for any tuning range and bandpass width. Its insert loss can be less than 1 dB.

Figure 1 illustrates the filter consisted of two collimators as input/output ports, two polarization displacers, two rotators and several PIFs consisted of a birefringent unit and a polarizer.

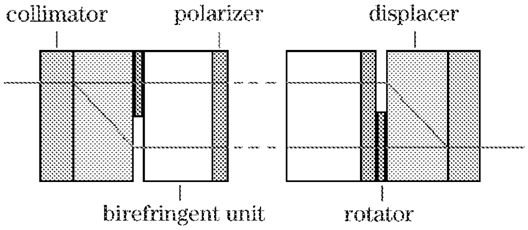

Fig. 1. The schematic diagram of the filter based on polarization interference filter.

Incident beam from the collimator is firstly splitted into o-ray and e-ray by a polarization displacer. The plane of o-ray polarization is rotated by 90 degrees with the rotator. Then the two ray beams have same polarization. Because there are 45 degrees angle between the two ray's polarization and the main optical axis of the birefringent unit, the two linearly polarized rays are further divided into sub-o-ray and sub-e-ray, which overlap in space. The polarization direction of following polarizer is parallel to the e/o-ray, but 45 degrees with the sub-o/e-ray. So polarization interference occurs at the polarizer. Consequently, the polarizer outputs only e-component and filters out o-component. So does the second PIF, the third PIF, etc. At the output end, another rotator rotates the plane of polarization of the lower e-ray by 90 degrees. So the two ray can be combined together. Consequently, output beam consists of only predetermined wavelength.

The characteristic of the PIF is the same as an interleaver[9]. It is known that one interleaver can double channel spacing. When the next PIF with OPDOE twice the first is cascaded, the channel spacing can be extended by 4 times. Therefore a new kind of filter can be obtained by several cascaded PIFs with proportional OPDOE. When each PIF's OPDOE is tuned proportionally and synchronously, a tunable filter is achieved.

The first birefringent unit length in the first PIF is assumed to be l_1. It introduces the OPDOE equal to $l_1 \times (n_e - n_o)$, n_e and n_o are respectively the e-ray and o-ray refractive index of the birefringent unit. The relative transmission[10] of the first PIF is

$$t_1^1(\lambda) = \cos^2[\pi \times l_1 \times (n_e - n_o)/\lambda], \quad (1)$$

where, λ is light wavelength. The relative transmission of six cascaded PIF is denoted by $T_6(\lambda)$,

$$T_6(\lambda) = t_6^{32}(\lambda) \times t_5^{16}(\lambda) \times t_4^{8}(\lambda) \times t_3^{4}(\lambda) \times t_2^{2}(\lambda) \times t_1^{1}(\lambda), \quad (2)$$

where, $t_i^j(\lambda) = \cos^2[\pi \times l_i \times (n_e - n_o)/\lambda]$ is the relative transmission of i-th PIF, $l_i = j \times l_1$, $j = 2^{i-1}$. OPDOE in each PIF meets the proportional relation: $l_6 = 2 \times l_5 = 4 \times l_4 = 8 \times l_3 = 16 \times l_2 = 32 \times l_1$. $T_6(\lambda)$ is illustrated in Fig. 2 as dotted line when $t_1(\lambda) = 36 \times \lambda$. The tuning range is equal to 43 nm. It is just the period of the first PIF whose OPDOE is equal to $36 \times \lambda$. $t_1(\lambda)$ is drawn in Fig. 2 as dash line. Therefore, the tuning range is dominated by the OPDOE in the first PIF.

The bandpass profile of the filter is illustrated in Fig. 3 as dotted line. The bandwidth at −0.5 and −30 dB are about 0.26 and 1.1 nm, respectively. $t_6(\lambda)$ is shown as dash line. The filter's bandpass width is slightly narrower than that of the last PIF. So the bandpass width mainly depends on the OPDOE in the last PIF. The crosstalk is less than −30 dB, which comes from adjacent channel.

Based on above feature, the tuning range can be extended two times by reducing the first PIF's OPDOE from $36\times\lambda$ to $18 \times \lambda$. Meanwhile, its bandpass width can be narrowed two times by increasing the last PIF's OPDOE from $64 \times 18 \times \lambda$ to $128 \times 18 \times \lambda$ Consequently, their OPDOEs from the first to the last are $18 \times \lambda$, $2 \times 18 \times \lambda$, $4 \times 18 \times \lambda$, $8 \times 18 \times \lambda$, $16 \times 18 \times \lambda$, $32 \times 18 \times \lambda$, $64 \times 18 \times \lambda$, and $128 \times 18 \times \lambda$, respectively. Figures 4(a) and (b) show that the tuning range is 86 nm, the bandpass width is applicable to 50-GHz channel spacing. The crosstalk is the same as above.

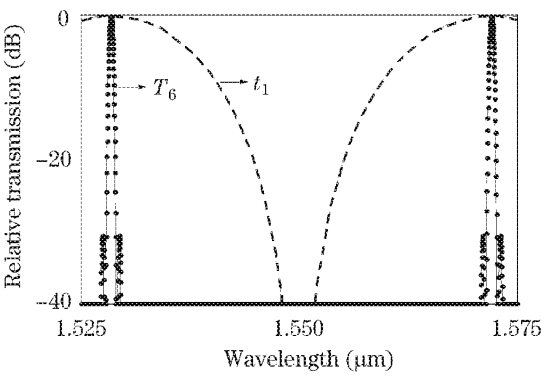

Fig. 2. The relative transmission of the filter (T_6: dotted line) with six cascaded PIFs and the first PIF (t_1: dash line).

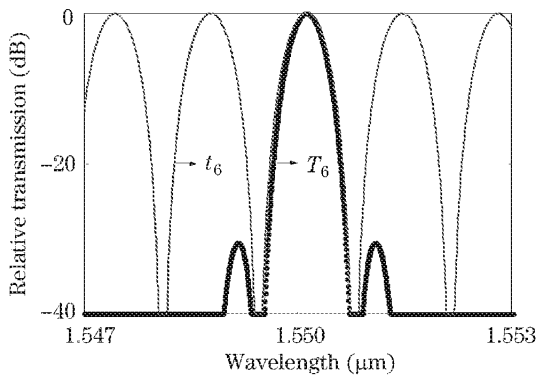

Fig. 3. The output profile of the filter (T_6: dotted line) with six cascaded PIFs and the sixth PIF (t_6: dash line).

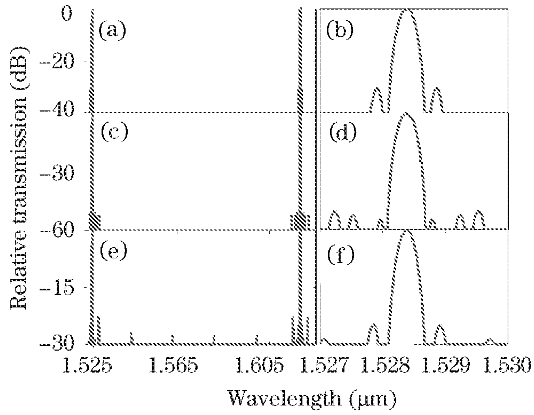

Fig. 4. The relative transmissions of filters with 86-nm tuning range and bandpass width applicable to 50-GHz application, but different crosstalk. (a), (b) −30 dB, corresponds to 8 cascaded PIFs; (c), (d) −50 dB, corresponds to 9 cascaded PIFs; (e), (f) −20 dB, corresponds to 7 cascaded PIFs.

The crosstalk comes from the adjacent channels. Adjacent channels attenuation mainly comes from the second PIF but one. However, the second PIF but one cannot sufficiently attenuate the adjacent channels. The crosstalk needs to be suppressed by additional PIF which can attenuate the crosstalk wavelength more. Analyzing the crosstalk wavelength, a set of PIF's OPDOEs is suggested that are l_1, $2 \times l_1$, $4 \times l_1$, $8 \times l_1$, $16 \times l_1$, $32 \times l_1$, $60 \times l_1$, $80 \times l_1$ and $128 \times l_1$ from the first to the last. Under the suggested OPDOE, the filter's transmission profile is illustrated in Figs. 4(c) and (d). The crosstalk is as low as −50 dB. Therefore, −50-dB crosstalk can be achieved by the way of adding additional PIF and OPDOE modification of the second PIF but one. The suggested set can be generalized as l_1, $2\times l_1$, $2^2 \times l_1$, $2^3 \times l_1$, $2^4 \times l_1$, $\cdots$, $2^{N-4} \times l_1$, $15 \times 2^{N-7} \times 1_1$, $10 \times 2^{N-6} \times l_1$ and $2^{N-2} \times l_1$, which suits for any tuning range and bandpass width. If the first PIF's OPDOE is decreased to $9 \times \lambda$ and the last PIF's OPDOE is increased to $512 \times 9 \times \lambda$, the filter is of 170-nm tuning range, −50-dB crosstalk, bandpass width applicable to 25-GHz channel spacing, it is consisted of 11 PIFs.

If −20-dB crosstalk is tolerable, seven cascaded PIFs are enough to achieve 86-nm tuning range and bandpass width applicable to 50-GHz channel spacing. The OPDOEs in each PIF are l_1, $2\times l_1$, $5\times l_1$, $10\times l_1$, $25\times l_1$, $50\times l_1$ and $125\times l_1$. The corresponding transmission profile is illustrated in Figs. 4(e) and (f).

In summary, a new kind of tunable optical filter is introduced for DWDM optical communication application. It is based on cascaded polarization interference filters. The tuning range and the bandpass width depend on the OPDOE in the first PIF and the last PIF, respectively. Hence, required bandpass width and tuning range can be easily achieved by designing their OPDOEs.

The crosstalk comes from the adjacent channels. As the output minimum wavelength of each PIF is definite, we can insert an additional PIF and modify the OP-

DOE in the second PIF but one. In this way, ultra-low crosstalk can be acquired. We suggest a set of OPDOEs that are l_1, $2\times l_1$, $2^2 \times l_1$, $2^3 \times l_1$, $2^4 \times l_1$, $\cdots$, $2^{N-4} \times l_1$, $15 \times 2^{N-7} \times 1_1$, $10 \times 2^{N-6} \times l_1$ and $2^{N-2} \times l_1$ from the first to the last. This set can yield the crosstalk as low as -50 dB and are applicable to any tuning range and bandpass width. The crosstalk is related to the OPDOE ratio. If a high crosstalk is tolerable, the needed cascaded PIFs will be less. As a result, the filter's performances associated with its transmission profile, including tuning range, bandpass width and crosstalk, can be designed. Its insert loss is due to surface reflection and the pair of collimators. Surface reflection is less than 0.01 dB when it is with AR coating. The insert loss can be less than 1 dB. In addition to its loose alignment requirement, there is no technology limit on the performances.

The OPDOE tuning can be realized by liquid crystal. Exact proportionate relations between PIFs are used in simulation in this paper. However, by means of electronics, only one wavelength OPDOE change in each PIF is enough. On the other hand, if multi-folded light path is used, not only the exact proportionate relation is met, also the footprint can be smaller.

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