Design of polarization-independent electro-optic multi-wavelength filter

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Abstract: In order to increase the flexibility of optical signal demultiplex, a polarization-independent two-port multi-wavelength tunable filter was designed based on the electro-optic effect of birefringent lithium niobate ($LiNbO_3$) crystal. On each arm of an asymmetric interferometer, mode-coupled electrode and phase-shifted electrode periodically alternated cascaded were set to realize mode conversion. **Z**-transform was utilized in analysis of Jones matrix to get the values of needed driving voltages to select wavelengths simultaneously. Narrow-band multi-wavelength with arbitrary distribution was simulated successfully in free spectrum range (FSR). 100% transmittance was obtained at each wavelength. The number of wavlengths had an influence on sidelobe of each wavelength. And sidelobe of 12 dB could be realized when three wavelengths were selected. Interleaver could also be obtained using this method, which had a flat passband and sidelobe of more than 20 dB.

Key words: optoelectronics device; polarization independence; multi-wavelength filter; **Z**-transform

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偏振无关的电光多波长滤波器设计

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摘　要:基于双折射铌酸锂($LiNbO_3$)晶体的电光效应,设计了一种偏振无关的二端口波导型多波长可调谐滤波器。在非对称干涉仪的上下分支波导上,耦合电极与相移电极周期性交叉级联实现模式的偏振转换。利用琼斯矩阵的 **Z** 域分析,求解驱动电压模拟实现多个波长的同时选择。仿真实现了自由光谱范围(FSR)内分布任意的窄带多波长输出。波长中心处传输率为 100%;旁瓣大小受到所选波长个数的影响,三个波长同时滤波的旁瓣可达 12 dB。同时得到了梳状滤波输出谱,其通带顶部平坦,旁瓣可达 20 dB 以上。

关键词:光电器件;　偏振无关;　多波长滤波;　*Z* 域变换

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0 Introduction

Application of multi-wavelength filter in wavelength division multiplexing system (WDM) improves the utilization rate of bandwidth and reduces the insertion loss in optical net nodes, so that WDM signal can be selected more flexibly. Many kinds of multi-wavelength filter have been reported, which are designed based on photonic crystals [1], aperiodically poled lithium niobate (APLN)[2], Febry-Perot cabity (F-P)[3-4], Mach-Zehnder interferometer (MZI)[5] and fiber grating[6] etc. And most of them are interleaver. Fourier transform used in electric signal processing becomes a new method in analysis of optical device [7-8]. In this paper, a polarization converter based on lithium niobate in **Z**-domain was designed. Using descrete Fourier transform (DFT), it was probably to get a multi-wavelength filter with arbitrary distribution. Also, an asymmetric interferometer was adopted to ensure polarization independence of the filter.

1 Principle and analysis

A schematic diagram of the filter on **X**-cut, **Y**-propogation lithium niobate ($LiNbO_3$) is illustrated in Fig.1. The **Y**-branches are symmetric 3 dB power splitters. And there is a half-wavelength diffence in the optical path between the upper and lower arms. On each arm, polarzation converter unit (PCU) is composed of cascade of mode-coupled electrode alternated with phase-shifted electrode. The basic period of interdigitated electrodes is Λ, with interval length **L** between every two coupled-mode electrodes. **G** is the gap between the phase-shifted electrode pair. Also, there is a relative spatial displacement of PCU in arms by $\Lambda/2$.

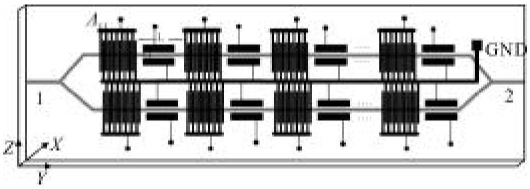

Fig.1 Schematic illustration of multi-wavelength filter

When an incident wavelength-multiplexed optical signal enters the input port 1, the intensity of guided light splits into two equal parts at the first **Y**-branch and is directed to the upper and lower PCU. If wavelength λ in the incident light satisfies the phase-match condition, polarization conversion occurs in each arm. Because of the half-wavelength difference in the optical path between the arms, the two lightwaves enter the second **Y**-branch with π phase difference. But at wavelength λ, an additional π phase difference is acquired through the relative displacement of $\Lambda/2$ the upper and lower PCU. As a result, wavelength λ appears in phase and combines to emerge from the output port 2, while all other wavlengths radiate into the substrate.

PCU is the core of multi-wavelength filter, which determines the filter characteristics and is controlled by the driving voltages. Utilizing **Z**-transform to solve the Jones matrix, we can get the needed voltage distribution. **N** cascaded PCU consists of **N** mode-coupled electrodes alternated with **N** phase-shifted electrodes. The Jones matrix of each mode-coupled section $\mathbf{C}_i$ and phase-shifted section $\mathbf{P}_i$:

$$\mathbf{C}_i=\begin{pmatrix} \cos(\mathbf{k}_i l) & -j\sin(\mathbf{k}_i l) \\ -j\sin(\mathbf{k}_i l) & \cos(\mathbf{k}_i l) \end{pmatrix} \tag{1}$$

$$\mathbf{P}_i=\begin{pmatrix} \mathbf{z}^{-1/2}\exp(-j\Delta\varphi_i/2) & 0 \\ 0 & \mathbf{z}^{1/2}\exp(j\Delta\varphi_i/2) \end{pmatrix} \tag{2}$$

where $\mathbf{k}_i$ is the coupling coefficient per unit length controlled by $\mathbf{V}_i^c$; $\Delta\varphi_i$ is the phase shift value controlled by $\mathbf{V}_i^p$ in the i-th network; l is the length of mode-coupled electrode. The voltages can be deduced [9]:

$$\begin{cases} \mathbf{V}_i^c=\mathbf{k}_i\lambda_0\Lambda/(4\pi\Gamma_{TE-TM}\sqrt{\mathbf{n}_{TE}^2\mathbf{n}_{TM}^3}\,\gamma_{51}) \\ \mathbf{V}_i^p=\Delta\varphi_i\lambda_0 G\Big/\pi L(\Gamma_{TE}\gamma_{33}\mathbf{n}_{TE}^2-\Gamma_{TM}\gamma_{13}\mathbf{n}_{TM}^2) \end{cases} \quad i=1,2,\cdots\mathbf{N} \tag{3}$$

where λ_0 is the center wavelength of free spectrum range (FSR); Γ_{TE}, Γ_{TM} and Γ_{TE-TM} are overlap factors of the applied electrical field with the waveguide optical field; γ_{51}, γ_{33} and γ_{13} are electro-optic coefficients.

So, after setting the desired filter transfer function $\mathbf{H}(\mathbf{z})$, we can use method of undetermined coefficients to solve the values of k_i and $\Delta\varphi_i$, so as to get the voltages.

$$\begin{cases} k_i=\arctan(m_1^{[i]}/n_1^{[i]})/l \\ \Delta\varphi_i=-\arg[(m_2^{[i]}/n_1^{[i]}-m_1^{[i]}/n_2^{[i]})/((m_1^{[i]})^2+(n_1^{[i]})^2)] \end{cases} \tag{4}$$

where $m^{[i]}$ and $n^{[i]}$ are the expansion coefficients of transfer functions $H(z)^{[i]}$ and $F(z)^{[i]}$ of i cascade PCU respectively; also $H(z)^{[i]}$ and $F(z)^{[i]}$ are reciprocal.

2 Simulation and discussion

In this paper, we get an interleaver and also a multi-wavelength filter which wavelengths can be combined with no rules through programming and simulation.

If we set the voltages driving phase-shifted electrodes zero, filtering output of interleaver can be obtained using the method above to get the values of voltages V_i^c. Each passband can be expressed by window function which determines the roll-off characteristic and sidelobe of passband. Figure 2 shows an interleaver centered at 1 550 nm when N = 33. Blackman window function is used to indicate the passband.

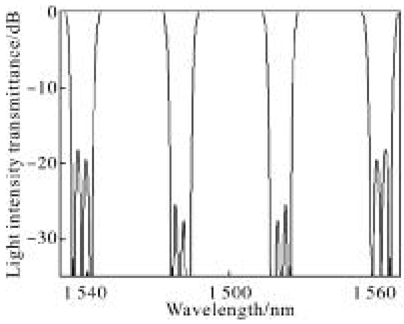

Fig.2 Output of interleaver

It can be seen that the output spectrum is symmetric centered of 1 550 nm. Each passband is flat, with bandwidth of 7 nm and sidelobe of more than 20 dB. Because there is a phase mismatch at the wavelengths away from 1 550 nm, sidelobe of passband there is a little higher. As a result, this method is suitable for small FSR. Also, transfer funcion $H(z)$ satisfies a linear-phase condition in the filter. So the group dispersion associated to interleaver is very small and can be negligible.

If we set the voltages driving phase-shifted electrodes nonzero, phase shift can be controlled along with the polarization conversion. So arbitrary multi wavelengths can be selected, with discrete Fourier transform (DFT) representing the desired filtering function.

Figure 3(a) shows the output of two wavelengths filter when N =19. In the range of about 8 nm centered of 1 550 nm, wavlengths λ_3 and λ_8 are selected simultaneously. Each wavelength can realized 100% transmittance, with 3 dB bandwidth of about 0.4 nm and sidelobe of more than 12 dB. Figure 3(b) shows the output of four wavelengths filter when N =19. Wavlengths λ_2, λ_4, λ_7 and λ_9 are filtered at the same time with sidelobe about 10 dB. So it can be deduced that number of wavlengths has an influence on sidelobe of each wavelength. And the 3 dB bandwidth is determined by the cascade stage N.

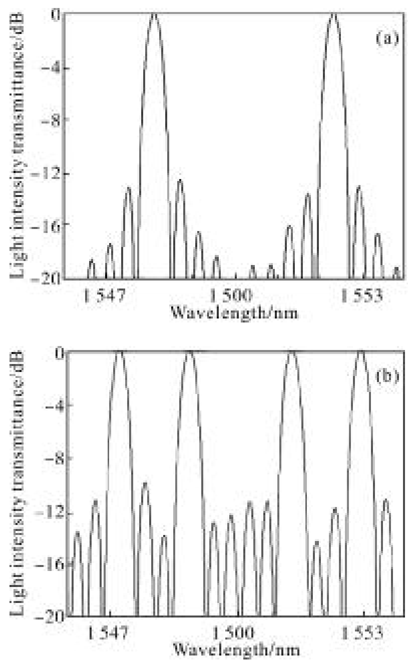

Fig.3 Ouput of two wavelengths filtering and ouput of four wavelengths filtering

3 Conclusion

A wave-guided electro-optic multi-wavelength filter is presented in this paper. An asymmetric interferometer is adopted so that the filter is polarization independent. The driving voltages are duduced by the Z-domain solution of transfer matrix. This filter can select wavelengths more flexibly. In addation, it can be tuned at submicrosecond speed based on the advantage of electro-optic tuning mode in $LiNbO_3$ [10], which is higher than some other filters like acousto-optic tunable filter (AOTF), F-P filter, M-Z filter and fibre Bragg grating filters based on thermal-optic effect and elasto-optic effect et al [11-14], so as to meet the need of high-speed and large-capacity optical networks.

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