A wide tuning range electro-optic filter based on long-period waveguide grating

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We present the design of an electro-optic filter with polarization insensitivity based on a long period waveguide grating. The filter exhibits an ultra-large wavelength tuning range of exceeding 35 nm and covering the whole C band (1530 to 1565 nm) in a bias voltage range from −84 to 84 V. In the whole tuning range, the transmission coefficients for quasi TE modes are over 97% and the 3 dB bandwidths are below 0.8 nm. The wavelength sensitivity to the tunable voltage is about 0.208 nm/V. This electro-optic filter can be used in dynamic WDM networks for fast wavelength scanning/selection, communication channel reconfiguration, and optical switching.

optical filter, long-period waveguide grating, electro-optic tuning, polarization insensitivity

Long-period fiber gratings (LPFGs) have attracted considerable attentions because of their numerous applications as filters and sensors. Of the many applications of LPFGs, the realization of tunable filters is of particular interest in fiber communication systems as such filters can potentially offer active control in optical networks [1]. Unfortunately, the resonance wavelength of an ordinary LPFG written in a conventional communication fiber shifts by only 3 to 10 nm for a change of 100°C in temperature [2], which is not sufficient for many applications. The difficulty of enhancing the tunability of a LPFG is very much due to the geometry and material constraints of the optical fiber. To relax the constraints of the optical fiber, long-period gratings formed in planar waveguides, referred to as long-period waveguide gratings (LPWGs), have been proposed [3]. The flexibility of the optical waveguide technology allows LPGs to be fabricated in different waveguide structures with different materials. This LPWG is superior to the LPFG tunable filters in both tuning range and sensitivity. The large thermo-optic coefficient of polymer has also been exploited for the realization of LPWGs with a tunable contrast at resonance wavelength. Chiang et al. [4] experimentally demonstrated that widely tunable LPWG fabricated in a polymer-clad ion-exchanged glass waveguide could provide linear wavelength tuning over the entire C+L band with a temperature control of only 10°C. However, the inherited drawback of thermo-optically tunable filters is their small tuning speed. In particular, tunable optical filters with fast tuning speed (nanosecond) are highly desired to perform packet- or cell-level switching and/or addressing in future highly dynamic WDM networks.

Tunable filters based on the electro-optic (EO) effect, such as EO micro-ring resonators, EO Fabry-Perot cavities, and EO fiber-Bragg-grating (FBG) [5–8], have the potential to achieve a fast tuning speed in nanosecond region. In this paper, we present an electro-optical filter design and numerically demonstrate that our filter has an ultra-large wavelength tuning range of exceeding 35 nm. Since it is based on EO effect, a high-speed wavelength tuning of a few nanoseconds can be expected.
1 The EO filter structure and physics

An LPWG tuning filter is shown schematically in Figure 1. The filter consists of two parallel identical rectangular single-mode cores with a refractive index $n_1$ as the input and output waveguides, respectively, which are separated by a distance $d$ and embedded in a rectangular cladding with thickness $t$ and width $s$ and a refractive index $n_2$. Each of the cores contains a corrugated grating with length $L$, corrugation depth $\Delta h$, and pitch $\Lambda$. The two gratings are perfectly aligned to each other. A pair of tuning electrodes is placed at the top and bottom interface of the cladding waveguide section to change the effective index of the input and output cores as shown in Figure 1(a).

The core materials are chosen to be the EO polymer APC/CLD-1 (Sigma Aldrich Co., USA) with $n_1 = 1.612$ for its high EO coefficient up to 43 pm/V [9,10]. The dimensions of the cores are fixed at $a = 3 \mu m$ and $h = 2 \mu m$, which ensure the single-mode operation at 1550 nm. The cladding is PMMA with $n_1 = 1.484, s = 6 \mu m$ and $t = 2.7 \mu m$, a material which causes no EO effect. The substrate is SiO$_2$/Si and its refractive index is 1.444. Because the evanescent field coupling between the two cores is no wavelength selectivity, $d$ should be chosen far apart enough to obtain specified wavelength coupling. It is easy to obtain the proper distance $d$ which is over 8 $\mu m$. The corresponding coupling process in the device involves [11]: (1) coupling between the guided mode of the input core and the cladding mode of the entire structure; (2) coupling between the cladding mode of the entire structure and the guided mode of the output core.

The transmission characteristics of a uniform LPWG can be analyzed by the coupled-mode theory [12]. The resonance wavelength $\lambda_0$, at which the coupling between the guided mode and the $m$-th order cladding mode is the strongest, is given by the phase-matching condition:

$$\lambda_0 = N_0 - N_m \Lambda,$$  

where $N_0$ and $N_m$ are the mode indices of the guided mode and the cladding mode, respectively, and $\Lambda$ is the grating pitch.

The transmission coefficient for the output core at the wavelength $\lambda_0$ is given by

$$T = \frac{\kappa^2 \sin^2 \left( \frac{\pi}{\Lambda} \right)}{\kappa^2 + \delta^2},$$

where $\delta = (2\pi/\Lambda)(\lambda_0 - \lambda)/\lambda$ is a detuning parameter that measures the deviation of the wavelength $\lambda$ from $\lambda_0$, $\kappa$ is the coupling coefficient that measures the grating strength, which is proportional to the spatial overlap in the grating region between the guided mode and the cladding mode, and $L$ is the length of the grating.

When a voltage is applied to the input core, the refractive index of the core will shift by $\Delta n = -0.5 \gamma_{33} \Delta V / T$, where $\gamma_{33}$ is the EO coefficient, $\Delta V$ is the applied tuning voltage, and $T$ is the total thickness of the waveguide core and cladding. The resonant wavelength shifted after a voltage change $\Delta V$ becomes

$$\lambda_0^* = \lambda_0 + \frac{d\lambda_0}{dV} \Delta V = (N'_0 - N'_m) \Lambda,$$

where $N'_0$ and $N'_m$ are the effective indices of the core and cladding modes after the voltage change $\Delta V$. Eq. (3) clearly shows that the resonance wavelength changes with the effective indices of the core and cladding modes at a given grating pitch. The bigger the difference of both effective indices is, the wider the wavelength tuning range is.

2 Theoretical analysis

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3 Design and analysis of the EO filter

The central task in the design of an LPWG filter is to determine the structure parameters of the grating, that is, the