Optics Communications 415 (2018) 13–17

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Design of multi-wavelength tunable filter based on Lithium Niobate

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A R T I C L E I N F O

Keywords:
Tunable filter
Lithium Niobate
Electro-optic effect
Waveguide gratings

A B S T R A C T

A multi-wavelength tunable filter is designed. It consists of multiple waveguides among multiple waveguide gratings. A pair of electrodes were placed on both sides of each waveguide. The tunable filter uses the electro-optic effect of Lithium Niobate to tune the phase caused by each waveguide. Consequently, the wavelength and wavelength spacing of the filter are tuned by changing external voltages added on the electrode pairs. The tunable property of the filter is analyzed by phase matching condition and transfer-matrix method. Numerical results show that not only multiple wavelengths with narrow bandwidth are tuned with nearly equal spacing by synchronously changing the voltages added on all electrode pairs, but also the number of wavelengths is determined by the number of phase shifts caused by electrode pairs. Furthermore, due to the electro-optic effect of Lithium Niobate, the tuning speed of the filter can reach the order of *ns*.

1. Introduction

Optical tunable filter is one of the basic components in optical applications, such as dense wavelength division multiplexing (DWDM) systems [1], tunable lasers [2,3] etc. With the rapid development of high-speed communication, there is an ever-increasing demand for tunable filter with fast tuning speed. Tunable filters based on acousto-optic effect and thermo-optic effect [4–7] offer a tuning speed in microsecond range. In order to improve the tuning speed, excellent electro-optical materials, such as Lithium Niobate (LN) have been used to achieve fast tunable filters [8–10].

In this paper we propose a multi-wavelength tunable filter by taking advantage of electro-optic effect of Lithium Niobate. Not only the wavelengths is tunable but also the number of wavelengths of the filter is adjustable.

2. Numerical model

The structure of multi-wavelength tunable filter is shown in Fig. 1. It consists of multiple waveguides intersected among multiple waveguide Bragg gratings. Multiple electrode pairs are placed on both sides of waveguides. The LN is X-cut or Y-cut to take advantage of its electro-optic coefficient of γ_{33}.

Transfer matrix method is used to analyze the properties of the filter. The transmission spectrum and the reflection spectrum of the filter are given by [11]:

$$T = \left| F_{11} - \frac{F_{12}F_{21}}{F_{22}} \right|^2 \text{ and } R = \left| \frac{F_{21}}{F_{22}} \right|^2 \tag{1}$$

where

$$F = \begin{bmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{bmatrix} = M_1 \cdot M_{L_1} \cdot M_2 \cdot M_{L_2} \dots M_{L_N} \cdot M_{N+1} \tag{2}$$

$$M_j = \begin{bmatrix} \cosh(\gamma h_j) - i\frac{\hat{\sigma}}{\gamma} \sin h(\gamma h_j) & -i\frac{\kappa}{\gamma} \sin h(\gamma h_j) \\ i\frac{\kappa}{\gamma} \sin h(\gamma h_j) & \cosh(\gamma h_j) + i\frac{\hat{\sigma}}{\gamma} \sin h(\gamma h_j) \end{bmatrix} \text{ and}$$
$$M_{L_s} = \begin{bmatrix} e^{-i\frac{\varphi_s}{2}} & 0 \\ 0 & e^{i\frac{\varphi_s}{2}} \end{bmatrix}. \tag{3}$$

Here $M_j (j = 1, 2, 3 \dots, N + 1)$ and $M_{L_s} (s = 1, 2, 3 \dots N)$ represent the transfer matrix of the jth Bragg grating with length of h_j and the transfer matrix of the sth waveguide with length of L_s, respectively. $\kappa = \pi \Delta n / \lambda$ is the coupling coefficient of waveguide grating, Δn is the depth of index modulation and λ is the wavelength of light in vacuum. $\gamma = (\kappa^2 + \hat{\sigma}^2)^{1/2}$. $\hat{\sigma} = 2\pi n_{eff}(1/\lambda - 1/\lambda_B)$ is the detuning from the Bragg wavelength

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https://doi.org/10.1016/j.optcom.2018.01.027
Received 28 September 2017; Received in revised form 12 January 2018; Accepted 14 January 2018

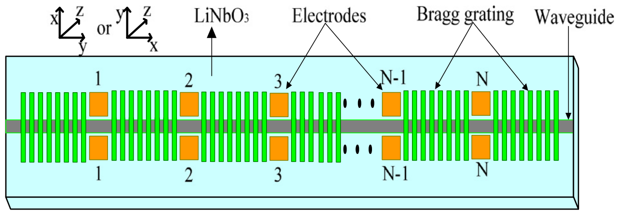

Fig. 1. Structure of multi-wavelength tunable filter.

$\lambda_B(\lambda_B = 2n_{eff}\Lambda)$, n_{eff} is the effective refractive index of waveguide Bragg grating. According to the electro-optic effect of LN [12], when voltage V_s is applied on L_s along z axis of LN, the phase shift φ_s caused by L_s is described as:

$$\varphi_s = \frac{4\pi n_e L_s}{\lambda}\left(1 - \frac{n_e^2 \gamma_{33} V_s \Gamma}{2d}\right) \quad (4)$$

where n_e is the effective refractive index of waveguide, d is the spacing of each electrode pairs, Γ is the overlap coefficient between the applied electric field and the optical field [13].

3. Simulation and discussion

To get the performance of the filter, the structure with three waveguide sections ($N = 3$) is analyzed by MATLAB simulation. In order to investigate the influence of each grating, set the total length of the four Bragg gratings $h = h1 + h2 + h3 + h4$ fixed and change the length of each grating. Set $n_{eff} = 2.1373$, $\Lambda = 362.6$ nm ($\lambda_B = 1550$ nm) and $\kappa = 10^{-3}$ μm^{-1} [14]. When $h = 1$ cm and $\varphi_s = \pi(s = 1, 2, 3)$, the reflection spectra of the sectioned Bragg gratings with different lengths and the transmission spectra of the corresponding filters are shown in Fig. 2.

From Fig. 2, when $h1$ and $h4$ is increased, the reflectivity of the grating increased, as a result, the extinction ratio of the filter is increased and the bandwidth of the filter is decreased. Thus, in order to get high extinction ratio, the reflectivity of the Bragg gratings on the two sides of the filter should close to 1. Besides, the resonant wavelength spacing is inverse proportional to the length of the Bragg gratings in the middle of the filter.

To investigate the tunable performance of the filter, an equivalent resonant cavity is used. Choose one waveguide as cavity, the structure on the left of the cavity is reflector1 and the structure on the right side of the cavity is reflector2. Fig. 3 shows the structure of the filter with L_2 as cavity. In Fig. 3 $\alpha(\lambda)$, $\beta(\lambda)$ and $\varphi_2(\lambda)$ are the phase caused by reflector1, reflector2 and the cavity, respectively. The filter will have resonance peak when the following phase matching condition is satisfied:

$$\alpha(\lambda) + \beta(\lambda) + \varphi_2(\lambda) = 2p\pi(p = 0, \pm1, \pm2 \ldots). \quad (5)$$

Set $\varphi_1 = \varphi_3 = \pi$, the phase spectrum of $\alpha(\lambda) + \beta(\lambda)$ is shown as the green dot line in Fig. 4. When $\varphi_1 = \varphi_2 = \varphi_3 = \pi$, the transmission spectrum of the filter is shown as the blue solid line in Fig. 4. It is shown that the resonant wavelengths have equal spacing and all the three resonant wavelengths satisfy the phase matching condition in Eq.(5).

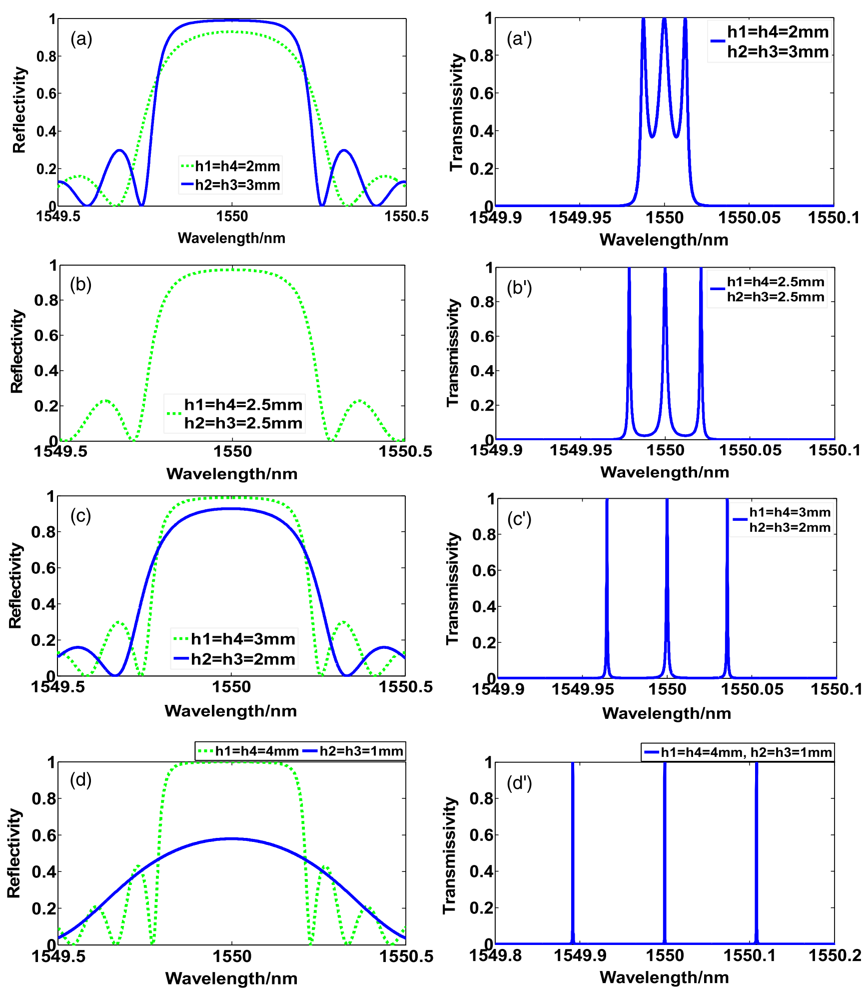

Fig. 2. (a)–(d) Reflection spectra of the sectioned Bragg gratings with different lengths, (a′)–(d′) transmission spectra of the corresponding filters.