Fibre-optic comb filter with tunable central wavelength and channel isolation at sub-microsecond speed

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Reported is a novel and compact tunable fibre-optic comb filter with the tuning implemented based on two electro-optic phase retarders made of lead magnesium niobate–lead titanate. Both the central wavelength and the channel isolation can be tuned at a sub-microsecond speed. A prototype filter with insertion loss of around −1.3 dB and channel isolation up to 26 dB is achieved.

Introduction: There has been considerable interest in recent years in the development of electronically tunable fibre-optic comb filters. Potential applications for these filters range from multi-wavelength laser sources [1] and wavelength division multiplexing (WDM) filters in reconfigurable optical networks to signal processors in microwave photonic systems [2]. The required characteristics of these filters include low insertion loss, large dynamic range, high tuning speed, compact, low power consumption and low cost. The practical realisation of an optical comb filter with tuning speed in the microsecond or even sub-microsecond range is hardly achievable by normal existing tuning schemes that are mainly based on electro-mechanical adjustment [3] or electro-optic (EO) effect in liquid crystal [4]. Recently, a tuning scheme based on a birefringence electro-optic modulator [5], and another employing a semiconductor optical amplifier (SOA) [6], were proposed so that a high tuning rate could be achieved. However, the approaches of [5] and [6], which rely on the hybrid structures with the composition of several fibre-optic devices, are complex, bulky and high cost. In addition, almost all tunable comb filters mentioned are unexceptionally referred to as central wavelength tuning. The tuning of other parameters such as channel isolation has not been addressed. In this Letter, we report a compact fibre-optic comb filter with tunable central wavelength and channel isolation based on two electrically controlled phase retarders made of bulky lead magnesium niobate–lead titanate (PMN-PT) transparent optic ceramics. A 100 GHz-spaced filter with low insertion loss, dynamic isolation and high tuning speed is demonstrated.

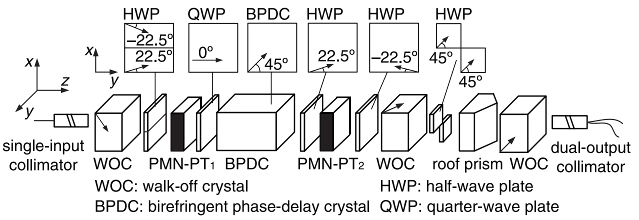

Fig. 1 *Schematic of proposed tunable optical comb filter*

Structure and design: Fig. 1 shows the schematic diagram of the proposed fibre-optic tunable comb filter. The compact filter is constructed and packaged with a single-input fibre collimator, three walk-off crystals (WOCs), four combined half-wave plates (HWPs), two electronically tunable phase retarders made of bulky PMN-PT material, a quarter-wave plate (QWP), a birefringent phase-delay crystal (BPDC), a roof prism and a dual-output fibre collimator. Fig. 1 also shows the optic-axes azimuth of crystals and wave plates as input lights transmitting along the z-axis. As well explained by Amman [7], the essential principle of a birefringent filter is that light originating in a single polarisation state can be made to interfere with itself when passing through birefringent crystals or birefringent fibres. In our structure, the first and the third walk-off crystals and the final HWP with the optic-axis at 45° establish the polarisation diversity paths that separate and later combine the orthogonally polarised light waves. Therefore, a complete polarisation-independent operation is ensured. The BPDC made of yttrium orthovanadate (YVO_4) is used to generate a phase delay between the ordinarily and extraordinarily polarised light waves within the crystal. An electrically controlled phase retarder PMN-PT$_1$ followed by the QWP is placed before the BPDC. Under the horizontal electric field along the y-axis within PMN-PT$_1$, linear polarised light waves from the input will interfere with themselves as light waves are decomposed into ordinary and extraordinary directions of polarisation states at the input surface of the BPDC. The interference tunes the channel isolation of the comb filter as a function of voltage to PMN-PT$_1$. The other phase retarder PMN-PT$_2$ with the same direction of electric field is placed after the crystal for the channel central wavelength tuning of the filter. The roof prism is used to deflect the two parallel output signal beams with a correct angle so that light beams can be coupled into the dual-output collimator.

The phase delay between the ordinarily and extraordinarily polarised light waves after travelling through the BPDC can be expressed as

$$\delta_0 = \frac{2\pi}{\lambda}\Delta n d \tag{1}$$

where Δn is the refractive index difference between the slow and fast axes of the crystal, d is the length of the crystal along the z-axis, and λ is the wavelength of the light wave. The EO effect in the PMN-PT is the quadratic Kerr effect [8]. When a voltage is applied, the resulting phase delay is given by

$$\Gamma = \frac{\pi t n^3 R V^2}{\lambda h^2} \tag{2}$$

where R is the EO coefficient, t the physical path length that the light wave travels in the material, h the distance between electrodes, n the refractive index in the absence of an electric field, and V the voltage applied to the PMN-PT. The relationship between the input and output polarisation vectors of the crystals, phase retards and wave plates can be described mathematically with the Jones matrix method. Ignoring the optic-axes alignment errors of the birefringent crystal and the wave plates, the transfer function of one output can be expressed as

$$T = \frac{1}{2} + \frac{1}{2}\cos\Gamma_1 \cdot \sin(\delta_0(\lambda) + \Gamma_2) \tag{3}$$

where Γ_1 and Γ_2 control the channel isolation and the central wavelength of the comb filter, respectively.

Experimental results and discussion: Fig. 2*a* shows the measured transmission spectra against voltage applied to PMN-PT$_1$. The insertion loss of the comb filter is about −1.3 dB. As can be seen, when the applied voltage V_1 changes the channel isolation is changed. The channel isolation is 23 dB when $V_1 = 0$ V, and it reaches a maximum of 26 dB when the applied voltage is $V_1 = 25$ V. Fig. 2*b* shows channel isolation against the applied voltage to PMN-PT$_1$. We can see that the channel isolation increases with increase of the applied voltage at the first stage and decreases monotonically when the applied voltage is greater than 25 V, until it reaches a minimum of 0 dB. According to our results, the channel isolation can be improved to reach a maximum by applying a voltage to PMN-PT$_1$ to compensate for the alignment errors between the optical axes of the BPDC and the wave plates.

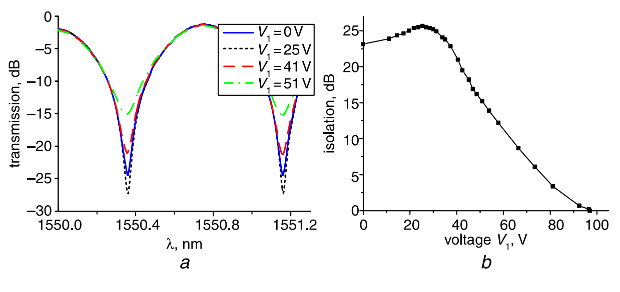

Fig. 2 *Measured transmission spectra against different operation voltages applied to PMN-PT$_1$, and channel isolation against applied voltage to PMN-PT$_1$*

a Measured transmission spectra against voltages
b Channel isolation against applied voltage

Fig. 3*a* shows transmission spectra measured for different voltages applied to PMN-PT$_2$. As the applied voltage increases, the central wavelength is shifted towards a longer wavelength. Fig. 3*b* shows that the central wavelength increases monotonically with increase of the driving voltage V_2. A central wavelength shift of a full channel spacing of 0.8 nm is reached when the voltage applied to PMN-PT$_2$ is about 195 V.

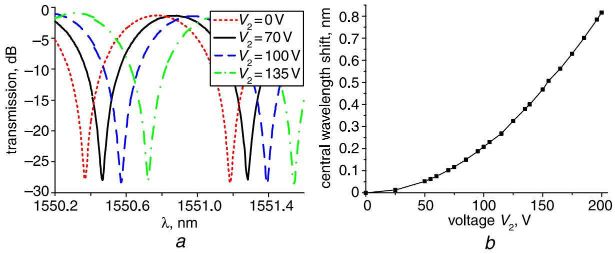

Fig. 3 *Measured transmission spectra for different voltages applied to PMN-PT$_2$, and central wavelength shift against applied voltage V_2*

a Measured transmission spectra for different voltages
b Central wavelength shift against applied voltage V_2

The transient response of the comb filter for applications in dynamic reconfigurable optical networks is investigated with the experimental setup shown in Fig. 4*a*. Two light waves with wavelengths λ_1 and λ_2 from two tunable laser sources are combined at a multiplexer and sent to the tunable comb filter. The signals from one output of the tunable comb filter are wavelength-demultiplexed and sent to two high-speed photodetectors (PDs). The output signals from the two PDs are monitored by an oscilloscope (Tektronix TDS7104). By setting $\lambda_1 = 1550.367$ nm and $\lambda_2 = 1550.767$ nm, the tunable comb filter can be used to separate λ_1 and λ_2 precisely to its two output ports. The detected optical signals from the two PDs with different wavelengths can be switched when a voltage of $\sim$140 V (half-wave voltage of the PMN-PT) is applied to PMN-PT$_2$. Fig. 4*b* shows the temporal response when a rectangular wave with a voltage of 140 V is applied to PMN-PT$_2$. The switching time is measured to be about 400 ns.

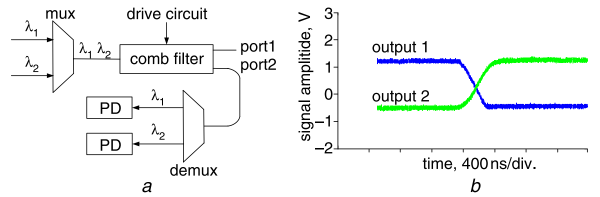

Fig. 4 *Experimental setup for evaluating tuning speed of comb filter and temporal response sampled from two PDs*

a Experimental setup
b Temporal response

Conclusion: We have proposed and demonstrated a compact and fast tunable optical comb filter with the tuning realised using two phase-retarders made of PMN-PT. Both the central wavelength and the channel isolation could be independently tuned at a sub-microsecond speed. The tuning of channel isolation provides more flexibility of operation and better performance for applications.

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One or more of the Figures in this Letter are available in colour online.

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