Electro-optic Solc-type wavelength filter in periodically poled lithium niobate

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We demonstrate an electro-optic Solc-type wavelength filter in periodically poled lithium niobate (PPLN). A Solc-type transmission spectrum is observed experimentally in PPLN with four periods from 20.2 to 20.8 μm. Modulation of the transmission power of the filter is realized by application of electric fields along the Y axis of the PPLN. It is observed that the wavelength can also be tuned by temperature. © 2003 Optical Society of America

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The Solc-type filter is well known as a polarization interference filter with birefringent crystals.[1,2] Usually, a Solc filter consists of a stack of identical birefringent plates with folded azimuth angles between crossed polarizers or fanned azimuth angles between parallel polarizers. An electrically active Solc-type filter can be fabricated by application of a periodic array of equal and opposite voltages to a thin platelet of $LiTaO_3$.[3] In the past decade, periodically poled lithium niobate (PPLN) has been widely studied in the field of nonlinear optical interactions because of its effective laser frequency conversion.[4,5] In PPLN, spontaneous polarization is periodically reversed by domain inversion. Besides the nonlinear optical coefficient, other third-rank tensors, such as the electro-optic (EO) coefficient, are modulated periodically because of the periodically reversed ferroelectric domains in PPLN.

In this Letter we find that, by applying a uniform dc electric field along the transverse (Y) axis of PPLN, a Solc-type filter can be realized. Compared with traditional Solc filters,[1–3] the PPLN EO Solc filter takes advantage of one-chip integration in lithium niobate and a simpler electrode structure. We demonstrate an EO Solc-type filter based on PPLN. In particular, we observe the amplitude modulation of the transmission power by applying an electric voltage along the transverse direction of the PPLN. In addition, the wavelength of the transmission light can be controlled by the temperature over a broad range.

In a folded Solc-type filter a series of half-wave plates are contained between crossed polarizers, with the optical axes of the half-wave plates alternately aligned at angles of $+\theta$ and $-\theta$ with respect to the plane of polarization of the input light.[1] The angle θ is called the rocking angle. At the fundamental wavelength of the filter each half-wave plate rotates the plane of polarization symmetrically by 2θ with respect to its optical axis. The fundamental wavelength is given by

$$\lambda_0 = \frac{2}{2m+1}(n_o - n_e)d\,, \qquad m = 0, 1, 2, \ldots, \qquad (1)$$

where n_o and n_e are refractive indices of the ordinary wave and extraordinary wave, respectively, and d is the plate thickness. After passing through the stack of half-wave plates, the optical plane of polarization rotates continually and emerges finally at an angle of $2N\theta$, where N is the number of plates. The transmission of the filter at wavelength λ_0 is $T = \sin^2(2N\theta)$. Therefore, when $2N\theta = 90°$ at the filter output, light of wavelength λ_0 does not experience loss in passing through the crossed analyzer. Light at other wavelengths does not satisfy the above condition and is therefore quickly attenuated at the crossed output polarizer. This is because the basic transfer function exhibits a $\sin x/x$ function dependence with a peak at wavelength λ_0. The FWHM of such a filter can be estimated with the following equation:

$$\Delta\lambda_{1/2} = 1.60\lambda_0/(2\nu + 1)N\,, \qquad (2)$$

where ν is the order of the half-wave plate.

In a lithium niobate crystal, because of the presence of an external electric field along the Y axis, the refractive-index ellipsoid deforms, and consequently the Y and Z axes of the Z-cut lithium niobate rotate by a small angle θ about the X axis. X, Y, and Z represent the principal axes of the original index ellipsoid of the lithium niobate crystal. The PPLN crystal was Z cut, and the light propagated along the X direction. The rotation angle θ is given by[1,2]

$$\theta \approx \frac{\gamma_{51}E}{(1/n_e^2) - (1/n_o^2)}\,, \qquad (3)$$

where E is the field intensity and γ_{51} is the EO coefficient. Note that the coefficient γ_{51} changes its sign in the negative domains because of the 180° rotation of the crystal structure. Thus, even in the presence of a uniform electric field along the Y axis, the rotation angle of the Y and Z axes changes sign from positive to negative domains. For a PPLN with alternately positive and negative domains whose length is given by $d = [(2m+1)/2][\lambda_0/(n_o - n_e)]$, where $m = 0, 1, 2, \ldots$, a folded Solc-type filter is easily formed by application of a uniform electric field along the Y axis. Since the rocking angle θ given by relation (3) is proportional to the intensity of the applied voltage, the transmission intensity at a given wavelength can be electrically modulated by the applied electric field. Furthermore,

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very narrow spectrum filters can be achieved by employment of a longer PPLN crystal, since the linewidth of the transmission spectrum is governed by both the number and the order of the half-wave plates.

Figure 1 is a schematic diagram of the experiment. A PPLN crystal is placed between two crossed polarizers. The arrows inside the PPLN indicate spontaneous polarization directions. A uniform electric field is applied along the Y axis of the PPLN sample. The PPLN in the experiment is fabricated by the electric field poling technique at room temperature. The sample with dimensions of 28 mm $\times$ 5 mm $\times$ 0.5 mm consists of four gratings with periods from 20.2 to 20.8 μm and a width of 1 mm. The polarization of the front (end) polarizer is along the Y (Z) axis. We use the EXEO Model IQ-12004 as a testing system for the optical device. It includes a tunable laser, a broadband amplified spontaneous emission source, a high-speed powermeter, and an optical spectrum analyzer.

According to the theoretical analysis mentioned above, in the absence of an applied voltage the effect of Solc-type filtering in PPLN should not exist. However, in our experiment such filtering is observed in the transmission spectrum of PPLN without an applied voltage. Figure 2 shows the measured output power versus the wavelength for the PPLN with periods of 20.6 and 20.8 μm at a temperature of 24 °C. For samples of 20.6- and 20.8-μm period a transmission peak is observed at wavelengths of 1516.80 and 1529.80 nm, respectively. The FWHM of the transmission spectrum is ~0.8 nm. For the 20.2- and 20.4-μm periods, we cannot detect the transmission peaks because of the limitation of the wavelength range of the tunable laser.

The length of each domain in the PPLN is 10.4 and 10.3 μm for the 20.8- and 20.6-μm periods, respectively. Each domain, according to Eq. (1), is equivalent to a zeroth-order half-wave plate for central wavelengths of 1525.5 and 1511.2 nm for the 20.8-μm and 20.6-μm periods, respectively. These wavelength values at 24 °C are calculated with the Sellmeier equation,[6] which differs from our experimental values. This discrepancy is possibly caused by the fact that the refractive index in our experiment may be different from the one in Ref. 6.

The experimental observation of the Solc filter indicates that there is a rocking angle ϕ between the optical axes of the positive and negative domains. However, the origin of this rocking angle is not clear. More work is needed to clarify this issue. When a rocking angle exists between domains, the input light, which is polarized along the Y axis, rotates by an angle of 2ϕ after passing through the first set of positive and negative domains. Thus, after passing through N domains ($N/2$ sets), the rotation angle of the polarization is $N\phi$. For the 20.8-μm-period PPLN the number of domains is ~2692. The transmission of the power is measured to be ~70% without an applied electrical field. According to the equation $T = \sin^2(N\phi)$, the rocking angle ϕ is calculated as $\phi = (m\pi \pm 0.991)/2692$ (in radians), where $m = 0, 1, 2, 3, \ldots$. The FWHM of the filter, which is calculated from Eq. (2) to yield $\Delta\lambda_{1/2} = 0.9$ nm, is in agreement with our experimental result of 0.8 nm.

The rocking angle formed by the electric field given by relation (3) does not account for the initial rocking angle ϕ between the axes of domains. In this case the electrical modulation behavior is described by $T = \sin^2(2N\theta)$, where θ is induced by the applied voltage, as calculated by relation (3). The calculated values of T at 24 °C without consideration of ϕ are plotted as a dashed curve in Fig. 3. The experimental results of the normalized transmission of the Solc filter (20.8 μm) as a function of the applied voltage at 24 °C are shown as a solid curve in Fig. 3. The overall change is that there is a phase shift between the two curves, with the phase difference of 0.991 rad, as seen from the shifted calculated curve (dotted curve) in Fig. 3. The slight deviations beyond the phase shift, including the different periodicity, may be caused by the voltage dependence of the initial ϕ and the uncertainty of the EO coefficient. The central wavelength at which the Solc-type filter is blocked occurs at the applied voltage of -1.2 kV. When the reverse voltage is decreased, the transmission of the light power increases as $\sin x$. At zero applied voltage, ~70% of the light power passes through the PPLN Solc filter. Further increase of the voltage continues to increase the transmission until it reaches almost 100% at $+0.75$ kV. Further higher voltage causes the transmission to decrease. We did not test our sample outside the range of -2.0 to $+1.2$ kV because of the possible damage to the PPLN at high voltage. From Fig. 3 we see that an amplitude modulator can be realized based on the

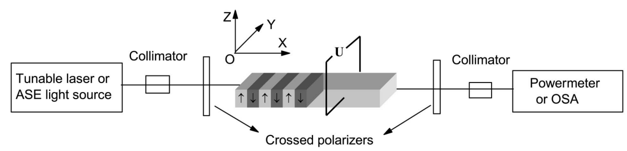

Fig. 1. Experimental setup for a PPLN Solc wavelength filter. A PPLN crystal is placed between two crossed polarizers. The PPLN crystal is Z cut, and the light propagates along the X direction. A uniform electric field is applied along the Y axis of the PPLN sample. ASE, amplified spontaneous emission; OSA, optical spectrum analyzer.

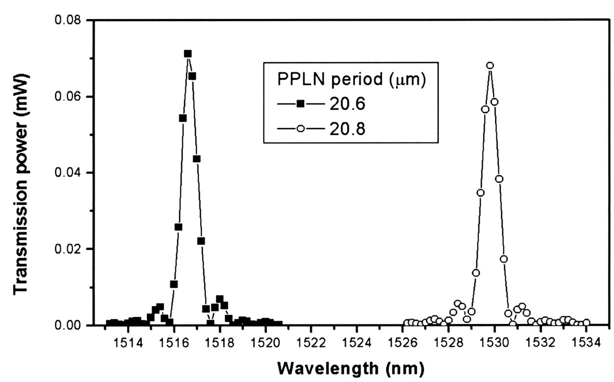

Fig. 2. Measured transmission power versus wavelength of the Solc filter in the 20.6- and 20.8-μm-period PPLN at a temperature of 24 °C. The FWHM of the transmission spectrum is ~0.8 nm.

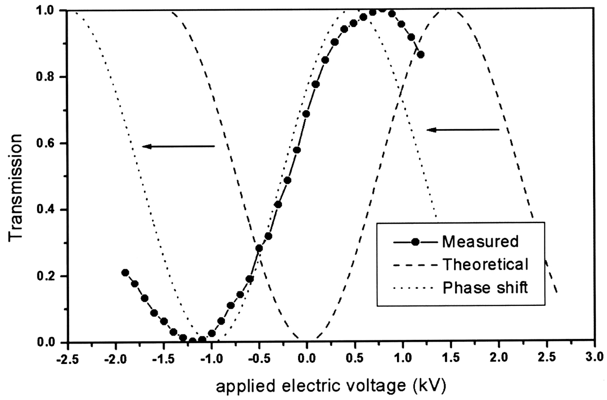

Fig. 3. Experimental measurement of the normalized transmission of the Solc filter (20.8 μm) as a function of the applied voltage at 24 °C for a given wavelength of 1529.80 nm. The solid curve is the experimental measurement, the dashed curve represents the theoretical values calculated from the Sellmeier equation from Ref. 6, and the dotted curve is phase shifted from the dashed curve for comparison with the experiment.

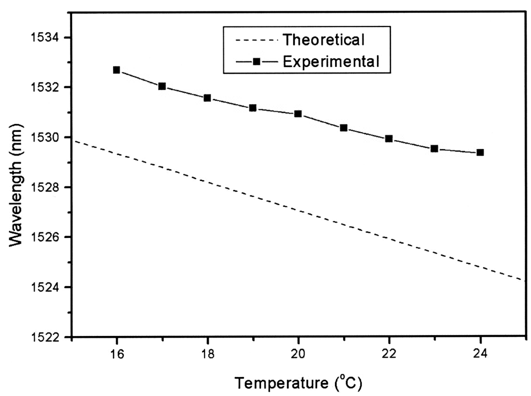

Fig. 4. Experimental measurement of the central wavelength of the Solc filter (20.8 μm) as a function of the temperature without the applied external electric voltage. The dashed line represents the theoretical values calculated from the Sellmeier equation from Ref. 6, and the solid curve is the experimental measurement.

electrically tunable Solc-type filter in PPLN with a half-wave voltage of ~1.95 kV.

The ordinary and extraordinary indices of lithium niobate are temperature dependent. From Eq. (1) the central wavelength can be tuned when the working temperature of the PPLN is changed. Figure 4 shows the temperature dependence of the central wavelength for the PPLN Solc-type filter (20.8 μm). When the temperature is increased from 16 to 24 °C, the central wavelength changes from 1532.67 to 1529.35 nm (shown as a solid curve). The linear fit shows that the tuning rate is 0.415 nm/°C. The dashed line in Fig. 4 is the theoretical temperature-tuning curve calculated with the Sellmeier equation from Ref. 6. Its temperature-tuning rate is 0.58 nm/°C, which is larger than that of the experimental measurement. The difference between the theoretical and experimental results may arise from the unknown data of the wavelength and temperature dependence of the refractive index of our PPLN sample. Wavelength tuning by temperature is interesting in dense wavelength division multiplexer optical fiber communication systems, where it can be employed as a wavelength-tunable filter for all-optical wavelength routing.

In conclusion, we have demonstrated an electro-optic Solc-type wavelength filter in periodically poled lithium niobate. The filtering effect exists even at zero applied voltage. The amplitude modulation is realized by tuning the applied voltage with a half-wave voltage of 1.95 kV. The dependence of the central wavelength shift on temperature shows a near-linear relationship, and the tuning rate is 0.415 nm/°C. We believe that this special electro-optical Solc-type wavelength filter may have potential applications in optical industries.

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