Characteristics of Sölc Filters in $\chi^{(2)}$ Nonlinear Photonic Crystals

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The characteristics of Sölc filters in $\chi^{(2)}$ nonlinear photonic crystals, periodically poled lithium niobate (LiNbO$_3$), were investigated by the Jones matrix method. The transmittance increases and the full width half maximum of the filter becomes narrow as the duty ratio increases. However, the filtering wavelength does not change. The transmittance at the filtering wavelength is over 95% when the duty ratio is larger than 0.35.

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Lithium niobate (LiNbO$_3$) has attracted much attention because of its large electro-optic and nonlinear optical coefficients. The improvement of electric poling techniques allows periodically poled lithium niobate (PPLN) to be very useful in the enhancement of conversion efficiency in optical second harmonic generation and other nonlinear optical processes [1,2]. Recently, it has been experimentally demonstrated that PPLN, so called $\chi^{(3)}$ nonlinear photonic crystals, acts as a folded Sölc filter composed of alternating birefringent plates [3], because there is a small angle between axes of positive and negative domains after the electric poling process [4]. Tunable Sölc filters based on PPLN have also been proposed. The tuning ability is due to the electro-optic, thermo-optics, and photovoltaic effects of LiNbO$_3$. Thus the filtering wavelengths of PPLN Sölc filters can be tuned by applying external voltage [5], illuminating ultra-violet light [6], and varying temperature [7,8].

The filtering wavelength of a Sölc filter usually depends on the thicknesses of birefringent plates. In the proposed PPLN Sölc filters, the thickness of a positive domain is equal to that of a negative one. However, the characteristics of PPLN Sölc filters have been rarely studied when the thickness of a positive domain is different from that of a negative one. In this paper, we investigated the transmission characteristics of PPLN Sölc filters by varying the duty ratio defined by the ratio of the thickness of a negative domain and a period of PPLN structure. The transmittance of the filters were simulated by the Jones matrix method [3].

We observed that the transmittance increases and the full width half maximum (FWHM) becomes narrow when the duty ratio increases. However, the filtering wavelength does not change, though the duty ratio is varied. The transmittance at the filtering wavelength is almost 100% when the duty ratio is between 0.4 and 0.5.

Figure 1 shows the schematic of experimental set-up for a PPLN Sölc filter that is placed between two crossed polarizers. It is worth introducing shortly the physical reason why a PPLN crystal acts as a folded Sölc filter. As mentioned above, there is an angle $\theta$ (-$\theta$)

**FIG. 1.** Schematic of experimental set-up for a PPLN Sölc filter.
between axis of positive (negative) domain and Z-axis and thus, the angle between optical axes of a positive and a negative domains is 20°. The input light polarized along the z direction rotates 49° after passing through the first positive and negative domains and finally, 2Nθ after passing through all the domains of N/2 periods. If this final rotation angle is π/2, the rotated light is polarized along the y direction and passes through the rear polarizer completely [3,4].

The transmission spectrum of a Sölle filter can be simulated by the Jones matrix. The components of the Jones matrix for a domain D are given by

\[ D_{11} = (\cos\Gamma/2 - i\cos2\psi \sin\Gamma/2)^2 + \sin^2\psi \sin^2\Gamma/2, \]
\[ D_{12} = \sin4\psi \sin2\Gamma/2, \]
\[ D_{21} = -D_{12}, \]
\[ D_{22} = (\cos\Gamma/2 + i\cos2\psi \sin\Gamma/2)^2 + \sin^2\psi \sin^2\Gamma/2, \]

where ρ is the angle between axis of a domain and Z-axis and Γ is the phase retardation of a domain. For \( \lambda, \Gamma = \pi(n_e - n_o)/\lambda \) where \( n_e \) and \( n_o \) are the extraordinary and the ordinary index of LiNbO₃, respectively [3]. The matrix multiplication for N domains results in the Jones matrix for a PPLN Sölle filter, M. The transmissivity of the filter is \( T = |M_{11}|^2 \) because the input and output lights are linearly polarized in the z and y directions, respectively.

Figure 2 shows the simulated transmission spectra of PPLN Sölle filters when the number of domains N is 500 (dotted line), 1000 (dashed line), and 2500 (solid line). The period of PPLN structure is 21 µm and the thickness of a negative domain is a half of the period, 10.5 µm. \( n_e (n_o) \) is chosen to be 2.15 (2.22). The transmission spectra show that the filtering wavelength is 1470.1 nm for all the cases and the FWHM becomes narrow as N increases. The theoretically derived formulas of the filtering wavelength \( \lambda_f \) and the FWHM of the Sölle filter \( \Delta \lambda_{1/2} \) are given by \( \lambda_f = (n_e - n_o)\Lambda/(2m - 1) \) (m = 1, 2, 3, ...) and \( \Delta \lambda_{1/2} \approx 1.6\lambda_f/N \), respectively, when the thicknesses of the domains are the same [3]. \( \lambda_f \) obtained from the formulas are 1470 nm when m = 1. The value is in excellent agreement with that from the simulated result. From the theoretical formula of \( \lambda_f \), one can see that the \( \lambda_f \) is very sensitive to the difference between \( n_e \) and \( n_o \) because Λ is order of \( 1 \times 10^5 \) nm. We observed that \( \lambda_f \) changed abruptly when the difference between \( n_e \) and \( n_o \) varies slightly from the simulations. \( \Delta \lambda_{1/2} \) from the simulated transmission spectra for N = 500, 1000, 1500, 2000, and 2500 (circles) are compared with the theoretical \( \Delta \lambda_{1/2} \) (dotted line) as shown in Figure 3. The simulated values are well matched to the theoretical ones.

We investigated the characteristics of PPLN Sölle filters when the thickness of a positive domain is different from that of a negative domain. We simulated the transmission spectra of the filters as the duty ratio increases. The duty ratio is the ratio between the thicknesses of a negative domain \( d_o \) and the period Λ, i.e., \( d_o/\Lambda \) (0 ≤ \( d_o/\Lambda \) ≤ 0.5). Figure 4 shows the transmission spectra of PPLN Sölle filters with N = 2000 when \( d_o/\Lambda \) = 0.1, 0.3 and 0.5. The transmittance increases and the FWHM of the filter becomes narrow as \( d_o/\Lambda \) increases. However, the filtering wavelength does not change. From the Jones matrix for a PPLN Sölle filter, we derived theoretically the filtering wavelength of the filter where the thickness of a positive domain, \( d_p \), is different from that of a negative domain, \( d_o \). The theoretical filtering wavelength \( \lambda_f = (n_e - n_o)(d_p + d_o)/(2m - 1) \), where \( d_p + d_o \) is a period of PPLN, Λ. Thus, the filtering wavelength does not vary under the condition that the period is not changed, although

![FIG. 2. Transmission spectra of a PPLN Sölle filter when the number of domains N=500 (dotted line), 1000 (dashed line), and 2500 (solid line). The period of PPLN structure is 21 µm and the thickness of a negative domain is a half of the period, 10.5 µm. \( n_e (n_o) \) is chosen to be 2.15 and 2.22, respectively.](image)

![FIG. 3. FWHM from the simulated transmission spectra for N = 500, 1000, 1500, 2000, and 2500 (circles) and FWHM from the theoretical formula (dotted line).](image)
FIG. 4. Transmission spectra of PPLN Sölc filters with \( N = 2000 \) and \( d_n/\lambda = 0.1, 0.3, \) and 0.5.

the thickness of a negative domain increases. We also studied the dependence of the transmittance at the filtering wavelength on \( d_n/\lambda \). Figure 5 shows that the transmittance increases as \( d_n/\lambda \) increases. We observed that the dependence of the transmittance on \( d_n/\lambda \) is identical to that of the transmittance on \( 1 - d_n/\lambda \). It is worth noting that the transmittance at the filtering wavelength becomes over 95% when \( d_n/\lambda \) is larger than 0.35. This behavior can be of benefit to the fabrication of PPLN Sölc filters.

In conclusion, we investigated the transmission characteristics of PPLN Sölc filters by changing the number of domains and the duty ratio. The FWHM of the filter becomes narrow as the number of domains increases. The FWHM of an order of \( 10^3 \) nm can be easily achieved in commercially PPLN structures with a few thousand domains. When the duty ratio increases, the transmittance of the filter increases and the FWHM of the filter gets narrow but the filtering wavelength is not changed. The transmittance at the filtering wavelength is almost 100% in the range of duty ratio from 0.4 to 0.5.

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FIG. 5. Dependence of the transmittance at the filtering wavelength on \( d_n/\lambda \).

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