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

Chul-Sik Kee* and Jongmin Lee

Nanophotonics Laboratory, Advanced Photonics Research Institute and School of Photon Science and Technology, GIST, Gwangju 500-712, Korea

Yeung Lak Lee

Nonlinear Optics Laboratory, Advanced Photonics Research Institute, GIST, Gwangju 500-712, Korea

The characteristics of Sŏlc filters in $\chi^{(2)}$ nonlinear photonic crystals, periodically poled lithium niobate (LiNbO₃), 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 (LiNbO₃) 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 $\chi^{(2)}$ nonlinear photonic crystals, acts as a folded Sŏlc 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 Sŏlc filters based on PPLN have also been proposed. The tuning ability is due to the electro-optic, thermo-optics, and photovoltaic effects of LiNbO₃. Thus the filtering wavelengths of PPLN Sŏlc filters can be tuned by applying external voltage [5], illuminating ultra-violet light [6], and varying temperature [7,8].

The filtering wavelength of a Sŏlc filter usually depends on the thicknesses of birefringent plates. In the proposed PPLN Sŏlc filters, the thickness of a positive domain is equal to that of a negative one. However, the characteristics of PPLN Sŏlc 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 Sŏlc 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 Sŏlc filter that is placed between two crossed polarizers. It is worth introducing shortly the physical reason why a PPLN crystal acts as a folded Sŏlc filter. As mentioned above, there is an angle θ (-θ)
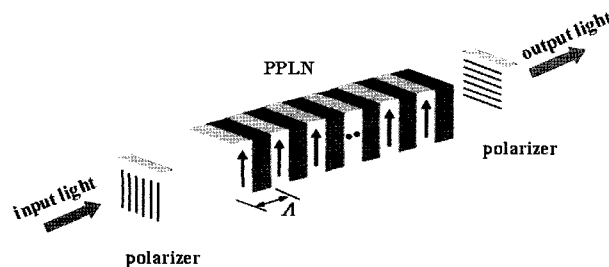

FIG. 1. Schematic of experimental set-up for a PPLN Sŏlc filter.

between axis of positive (negative) domain and Z-axis and thus, the angle between optical axes of a positive and a negative domains is 2θ. The input light polarized along the z direction rotates 4θ after passing through the first positive and negative domains and finally, $2N\theta$ after passing through all the domains of $N/2$ periods. If this final rotation angle is $\pi/2$, the rotated light is polarized along the y direction and passes through the rear polarizer completely [3,4].

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

$$D_{11} = (\cos\Gamma/2 - i\cos2\rho\sin\Gamma/2)^2 + \sin^2 2\rho\sin^2\Gamma/2,$$
$$D_{12} = \sin4\rho\sin^2\Gamma/2,$$
$$D_{21} = -D_{12},$$
$$D_{22} = (\cos\Gamma/2 + i\cos2\rho\sin\Gamma/2)^2 + \sin^2 2\rho\sin^2\Gamma/2,$$

where ρ is the angle between axis of a domain and Z-axis and Γ is the phase retardation of a domain. For λ, $\Gamma = \pi(n_e - n_o)\Lambda/\lambda$ where n_e and n_o are the extraordinary and the ordinary index of $LiNbO_3$, respectively [3]. The matrix multiplication for N domains results in the Jones matrix for a PPLN Sölc filter, M. The transmissivity of the filter is $T = |M_{21}|^2$ 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 Sölc 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 trans-

mission 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 λ_f and the FWHM of the Sölc filter $\Delta\lambda_{1/2}$ are given by $\lambda_f = (n_e - n_o)\Lambda/(2m - 1)$ $(m = 1,2,3\cdots)$ and $\Delta\lambda_{1/2} \approx 1.6\lambda_f/N$, respectively, when the thicknesses of the domains are the same [3]. λ_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 λ_f, one can see that the λ_f is very sensitive to the difference between n_e and n_o because Λ is order of 1×10^4 nm. We observed that of λ_f changed abruptly when the difference between n_e and n_o varies slightly from the simulations. $\Delta\lambda_{1/2}$ from the simulated the 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 Sölc 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_n and the period Λ, i.e., d_n/Λ $(0 \le d_n/\Lambda \le 0.5)$. Figure 4 shows the transmission spectra of PPLN Sölc filters with N = 2000 when $d_n/\Lambda = 0.1$, 0.3 and 0.5. The transmittance increases and the FWHM of the filter becomes narrow as d_n/Λ increases. However, the filtering wavelength does not change. From the Jones matrix for a PPLN Sölc 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_n. The theoretical filtering wavelength is $\lambda_f = (n_e - n_o)(d_p + d_n)/(2m - 1)$, where $d_p + d_n$ is a period of PPLN, Λ. Thus, the filtering wavelength does not vary under the condition that the period is not changed, although
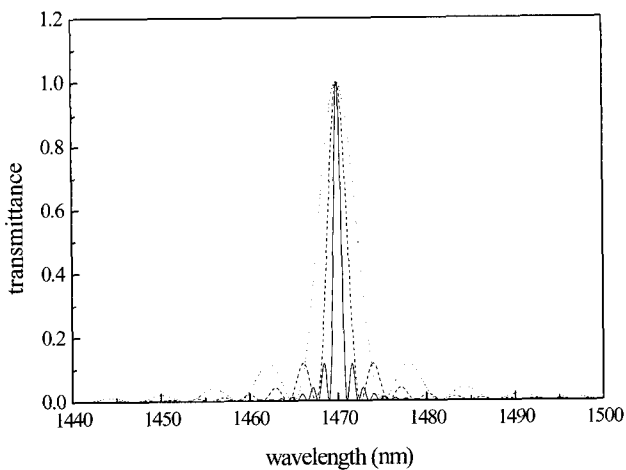

FIG. 2. Transmission spectra of a PPLN Sölc filter when the number of domains N=500 (dotted line), 1000 (dashed line), and 2500 (solid line). The period of PPLN structure is 21 μm and the thickness of a negative domain is a half of the period, 10.5 μm. n_e and n_o is chosen to be 2.15 and 2.22, respectively.
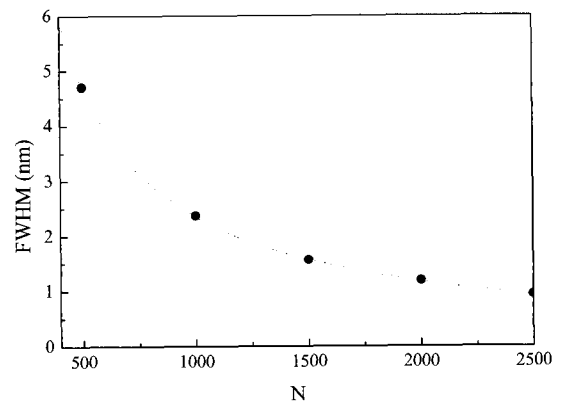

FIG. 3. FWHM from the simulated transmission spectra for N = 500, 1000, 1500, 2000, and 2500 (circles) and FWHM from the theoretical formula (dotted line).
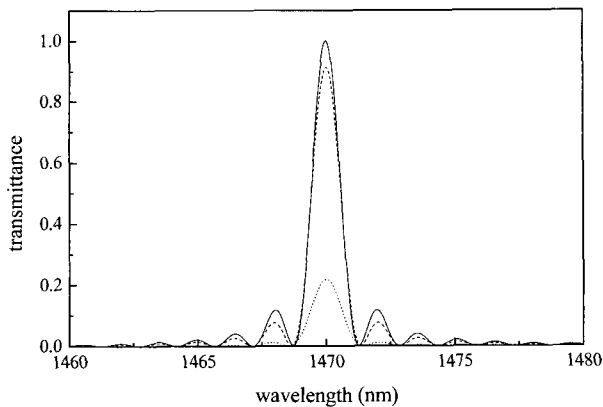
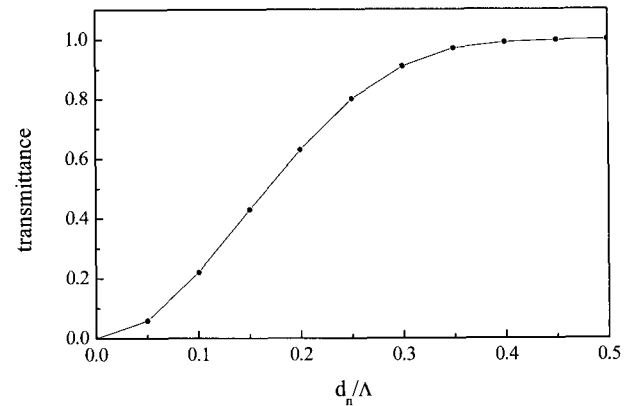FIG. 4. Transmission spectra of PPLN Sölc filters with $N = 2000$ and $d_n/\Lambda = 0.1$, 0.3, and 0.5.

FIG. 5. Dependence of the transmittance at the filtering wavelength on d_n/Λ.

the thickness of a negative domain increases. We also studied the dependence of the transmittance at the filtering wavelength on d_n/Λ. Figure 5 shows that the transmittance increases as d_n/Λ increases. We observed that the dependence of the transmittance on d_n/Λ 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/Λ 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^{-1} 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.

*Corresponding author: cskee@gist.ac.kr

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