Novel step-chirped quasi-phase matched gratings for broadband frequency doublers with high-efficiency flat response in nonlinear optical waveguides

***Amirhossein Tehranchi*[1], *Raman Kashyap*[1,2]**

Advanced Photonics Concepts Laboratory, Department of Electrical Engineering[1] and
Department of Engineering Physics[2], École Polytechnique, University of Montreal
C.P. 6079, Succ. Centre-ville, Montreal H3C 3A7, Canada. Tel. 514 340-4711, Fax. 514 340-5892.
amirhossein.tehranchi@polymtl.ca, raman.kashyap@polymtl.ca

Abstract

Novel step-chirped gratings (SCG) for broadband frequency doublers based on quasi-phase matched second harmonic generation in lithium niobate waveguides have been theoretically modeled and simulated for the first time to our knowledge. It is shown using apodized SCG flattens the bandwidth of ordinary SCG and the flatness can be improved extensively with apodization ratio. Moreover, in the SCG structure, increasing the chirp period and duty cycle may provide a more convenient method for fabrication and poling. Also, using a singly pump-resonant waveguide, the efficiency of an apodized SCG increases substantially especially in low loss waveguides.

1. Introduction

Frequency doublers using nonlinear optical waveguides in lithium niobate have been extensively studied over the past years. There has been increasing interest in broadening the bandwidth of such waveguide-based second harmonic generation (SHG) devices [1-2] because there are many applications in pulse compression and ultrafast optical signal processing [3]. Some work has been done on waveguide structures to increase the bandwidth and modified QPM grating structures have been proposed to broaden the phase matching bandwidth [4], although the bandwidths are still not adequate and waveguide devices have not been demonstrated. However, there still exists a need for higher conversion bandwidth, e.g., more than 30 nm. The use of a chirped grating structure for SHG instead of a uniform period one offers the benefit of a larger bandwidth. However, there exist three problems using chirped gratings. The first problem is the smallness of change in the linear-chirped grating (LCG) period which is typically around 100 picometer or less for a converter with a large bandwidth of several nanometers. We believe that the SCG can solve this problem. Using the SCG enables us to increase the period change, increasing the convenience of fabrication, while the bandwidth and efficiency remain almost the same in comparison to the LCG. The second problem is the noticeable ripples on the conversion efficiency curves for SHG. Our approach to solve this problem is the imposition of some apodization. This can be done by changing the duty ratio of the poled regions which helps to remove the ripples and achieves a nearly flat response. The third problem goes back to the low efficiency of SHG in SCG structure. This problem may be solved with resonant waveguides. Fabry-Perot type cavity is possible in a waveguide SCG-SHG device fabricated by imposing cavity mirrors directly on the waveguide facets. Using this method, strong improvement in the efficiency is anticipated. In this paper, we propose the engineering of the SCG in such a way as to broaden the bandwidth with larger step changes in chirp period. Also, we consider an effective method to apodize and nearly flatten the second harmonic conversion efficiency bandwidth by using increasing and decreasing patterns of inverted domains into the QPM gratings on poled lithium niobate waveguides, for fabrication based on annealed proton exchanged (APE) waveguides. Further, we show that by assuming singly pump-resonant waveguides, it is possible to increase the efficiency, whilst maintaining the other beneficial features.

2. Bandwidth Enhancement and Response Flattening

Advanced waveguide based frequency doublers take advantage of quasi-phase matching (QPM). A step-chirped grating is a structure enabling us to obtain wide phase matching bandwidth in QPM-SHG devices which is not flat but has ripples. To achieve a wide bandwidth and flat response, an apodized step-chirped grating structure is proposed as shown in Fig. 1. In this structure, the total grating length L_t has been divided into several sections of constant period but slightly chirped, each with a different step of $\Delta\Lambda$ between the adjacent sections. The central region with the length L is composed of p sections with 1:1 duty ratios.

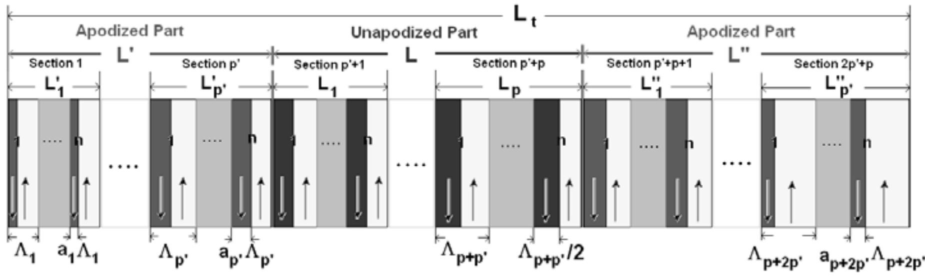
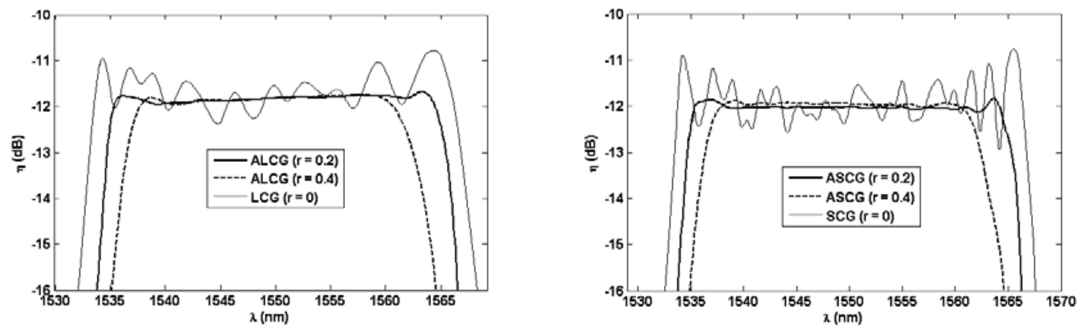


Fig. 1. Scheme of QPM-ASCG structures with increasing and decreasing parts of inverted domains.

Each of the two adjacent sides have apodized regions with the lengths L' and L'' consisting of p' sections. At the input, a constant duty ratio for each section is $a_s = s/2p', (s = 1,2,..., p')$ and changes symmetrically towards the exit. Each section, m consists of n periods, so $L_m = n\Lambda_m$ where $\Lambda_m = \Lambda_1 + \Delta\Lambda(m-1)$, $(m = 1,2,..., p + 2p')$ with Λ_1 as the period of the first section. To obtain the total second harmonic (SH) wave and efficiency, we can consider $p + 2p'$ uniform gratings. The propagations begin and cascade from the first section with the length L_1' to the last one with the length $L_{p'}''$. The channel waveguide is assumed to have a uniform cross section. The condition for QPM in the first section is $\beta_{2\omega} - 2\beta_{\omega} = 2\pi/\Lambda_1$ where β_{ω} and $\beta_{2\omega}$ are the mode propagation constants of the pump and second harmonic waves, respectively. $\Lambda_1 = (\lambda/2)/(N_{2\omega} - N_{\omega})$ is the period of the first section. N_{ω} and $N_{2\omega}$ are the effective mode indexes of the pump and SH waves in the $LiNbO_3$ waveguide, respectively. The QPM period of the grating is calculated by finding the effective indexes of waveguides and using Sellmeier expression in $LiNbO_3$. Assuming the grating has a binary modulation, the effective SHG coefficient of the region within a grating period in each section can be written as $d_m = (2d_{33}/\pi)\sin(\pi a_m)$ where d_{33} is the SHG coefficient of $LiNbO_3$. Thus, in each section we have a uniform grating but with slightly different d_m from its adjacent section by changing the duty ratio a_m which denotes the ratio of one region to the period. Consequently, this model of the typical domain-inverted QPM gratings has increasing and decreasing duty ratios and normalized effective SHG coefficients, at the beginning and at the end of the structure. According to Fig. 1, $r = (L' + L'')/L_t$ is the apodization ratio or the ratio of the total length with varying effective SHG coefficients to the total length of the structure. r=0 implies an unapodized device while for r=0.2 and r=0.4, one can find partially apodized devices. Here, the governing coupled mode equation is solved numerically with full pump depletion [5]:

$$\begin{aligned} \frac{d}{dz}A(z) &= -j\kappa^* A^*(z) B(z) e^{-j(2\Delta k)z}, \\ \frac{d}{dz}B(z) &= -j\kappa \left[A(z)\right]^2 e^{+j(2\Delta k)z}, \end{aligned} \tag{1}$$

where A and B are the amplitudes of the pump and the SH waves, respectively and $2\Delta k$ is the phase mismatch parameter of each section defined as $2\Delta k = \beta_{2\omega} - 2\beta_{\omega} - 2\pi/\Lambda_i$. Also, $\kappa = \frac{\omega}{2}\iint \left[E_{2\omega}(x,y)\right]^* d_m \left[E_{\omega}(x,y)\right]^2 dxdy$ is the coupling coefficient. $E_{\omega}(x,y)$ and $E_{2\omega}(x,y)$ are the normalized mode profiles for the fundamental harmonic (FH) and SH waves, respectively. The SHG conversion efficiency is defined as, $\eta = P_{out}/P_{in} = |B(L)|^2/|A(0)|^2$. Based on the apodization approach, the enhancement of conversion efficiency and reduction of ripples in the efficiency response of SHG-based frequency doubler by the changing of the duty ratio of inverted domains at the beginning and end parts of QPM gratings are demonstrated. Here, the nonlinear optic coefficient of lithium niobate d_{33} and the fundamental input power are assumed $25\,p\text{V/m}$ and $50\,\text{mW}$, respectively. Also, the data of z-cut poled $LiNbO_3$ are used in the numerical calculations. For APE waveguide, the effective cross section and refractive index difference are assumed $4\,\mu\text{m}^2$ and 0.09, respectively. Also, we have $L_t \approx 51\,\text{mm}$, $np_t = 3500$ and $\Lambda_1' = 14303\,n\text{m}$.



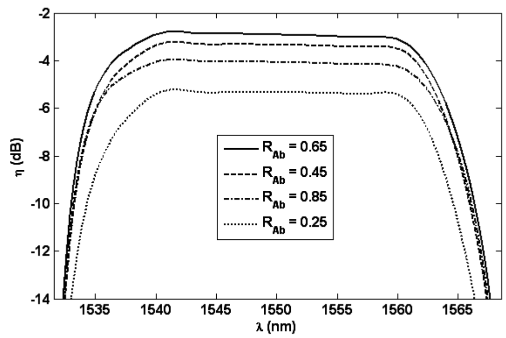
(a) (b)

Fig. 2. Comparison of (a) LCG and ALCGs; and (b) SCG and ASCGs for the different apodization ratios.

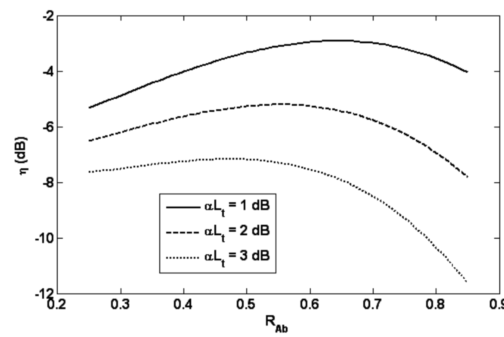
Figure 2(a) illustrates the efficiency of the LCG and ALCG ($n = 1$) versus the FH wavelength and gives a comparison between them for different *r* when $\Delta\Lambda = 0.075\,\text{nm}$. It shows how the ripples and spectral ears of the ALCG can be suppressed with increasing apodization ratios. Also, the slight slope between the ears in ALCG can be compensated by the ASCG. Figure 2(b) depicts the efficiency of the SCG and ASCG ($n = 10$) versus the FH wavelength and compares them when $\Delta\Lambda = 0.75\,\text{nm}$. It shows how the ripples of the ASCG may also be suppressed with increasing *r*. For a small apodization ratio, $r = 0.2$, the efficiency is nearly ripple-free with the bandwidth of about 32 nm except for the two residual "ears" at the edges. The maximum flat efficiency of about -12 dB can be achieved for both cases, while ASCG needs a smaller chirp step in comparison to ALCG. Further suppression of these spectral ears can be achieved by introducing longer apodization regions. For $r = 0.4$, the nearly flat bandwidth of about 30 nm and the maximum flat efficiency of about -12 dB can be achieved. It is seen that with increasing *r,* it is possible to obtain improved and different forms of efficiency curves with decreased bandwidths. In fact, the comparison between Figs. 2(a) and 2(b) implies that if the chirp period changes to one-tenth, and the sections increase tenfold changing the SCG into the LCG, the results are approximately the same. Thus, to achieve the same result, the apodized LCG needs smaller chirp period in comparison to the apodized SCG. On the other hand, for the same length, the ASCG reduces the number of sections and therefore increases the changes in the number of the poled region or the duty cycle [6]. Thus, increasing the change in the chirp period and the change in the duty cycle makes the fabrication of the apodized step-chirped gratings more convenient.

3. Efficiency Enhancement

With a simple arrangement, Fabry-Perot type cavity enables us to construct ASCG-SHG waveguide achieved by imposing cavity mirrors on waveguide facets. Cavity mirrors are applied to the front and back facets of travelling-wave waveguide SHG devices. The power reflection for the FH and SH are denoted by R_{Ab} and R_{Bb} for the back mirror and by R_{Af} and R_{Bf} for the front mirror, respectively. Here, they are assumed invariant over the bandwidth in our calculations. Singly pump-resonant ASCG-SHG waveguides ($R_{Ab}R_{Af} \neq 0$ and $R_{Bf} = R_{Bb} = 0$) are considered here and numerically characterized as their realization is more convenient and self-pulsation and bistability of the harmonic output are not expected in these structures. In the singly pump-resonant waveguide, a pump wave is launched from the back side, propagating back and forth in the waveguide cavity, and SHG interaction occurs. However, for an efficient resonant device, the phase matching condition for SHG and resonance condition for the FH wave must be satisfied simultaneously. Also, we consider that the coupling coefficient for forward SHG is equal to that for backward SHG. Figure 3(a) shows the efficiency for the singly pump-resonant ASCG waveguide for different R_{Ab} when $R_{Af} = 1$ and the total FH waveguide loss of $\alpha L_t = 1\text{dB}$. With increasing the reflectivity of pump at the back mirror, the efficiency improves and reaches the maximum of $\approx -3\text{dB}$ for $R_{Ab} \approx 0.65$ and decreases again with increasing of R_{Ab} . In the best case, a 9-dB improvement in efficiency can be achieved. Figure 3(b) depicts the efficiency versus R_{Ab} for different amounts of FH waveguide loss stating that the high efficiency is obtained for low loss waveguides. Also, it is observable that for the greater FH loss, the optimum value of R_{Ab} to achieve the maximum efficiency can be obtained at lower reflectivities.



(a)



(b)

Fig. 3. Efficiency of the singly pump-resonant ASCG waveguide (a) versus FH wavelength λ for $\alpha L_t = 1\text{dB}$ and (b) versus R_{Ab} for different waveguide FH loss. $R_{Af} = 1$ and $L_t \approx 51\text{mm}$ for both figures.

4. Conclusion

An effective method is proposed to broaden and flatten the frequency doubling bandwidth by apodizing or introducing increasing and decreasing patterns of inverted domains of QPM gratings in poled lithium niobate waveguides. We have shown the efficiency curve can be dramatically smoothed and flattened with the ripples being reduced to less than ±0.05 dB and the spectral ears can be significantly suppressed at the cost of longer apodization lengths. Moreover, to achieve the same bandwidth at the same efficiency, the ASCG has a flatter response and needs larger chirp steps (desirable for fabrication) in comparison to the ALCG. Also, using singly pump resonance, the efficiency of an ASCG increases dramatically especially in low loss waveguides. Maximum SHG efficiency of 1000%/W and flat bandwidth of 30 nm with a ~51-mm length structure can be achieved using an ASCG and singly pump-resonant waveguide. We believe that the combination of engineered ASCG and resonant waveguides are highly flexible techniques for the design and for easing the fabrication requirements of highly efficient and broadband frequency doublers.

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6. References

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