Efficient Broadband Frequency Conversion Using Engineered Apodized $\chi^{(2)}$ Gratings and Fundamental Harmonic Resonance

Raman Kashyap[1,2,3], Amirhossein Tehranchi[1,2] , and Chang-Qing Xu[4]
Advanced Photonics Concepts Laboratory, Radiofrequency Electronics Research Center (CREER)[1],
Department of Electrical Engineering[2], and Department of Engineering Physics[3], Ecole Polytechnique,
University of Montreal, C.P. 6079, Succ. Centre-ville, Montreal H3C 3A7, Quebec, Canada
Phone: +1 (514) 340 4711, Fax: +1 (514) 340 5892
Department of Engineering Physics[4], McMaster University, Hamilton, Ontario, Canada
raman.kashyap@polymtl.ca, amirhossein.tehranchi@polymtl.ca, cqxu@mcmaster.ca

Abstract
Apodized step-chirped grating in quasi-phase matched lithium niobate waveguide with fundamental-harmonic resonance are proposed and designed for efficient broadband frequency converters. The optimized values of back-facet reflectivity and input power are calculated to achieve maximum efficiency.

Introduction
Broadband frequency converters based on second harmonic generation (SHG) in lithium niobate waveguides have been studied over the past years because there are many applications in pulse compression and ultrafast optical signal processing [1,2]. We intend to use them as additional sources promising to perform dual-band optical coherence tomography (OCT) utilizing fundamental and second harmonic waves together, to allow enhanced diagnostic capability [3], as well as sources for temperature independent display applications. Modified QPM gratings have been proposed to broaden the phase matching bandwidth [4,5], although such converters are still not available.
We recently proposed the engineering of chirped gratings in such a way as to broaden flexibly the bandwidth of frequency doublers to provide a flattop response [6]. In the proposed apodized step-chirped grating (ASCG), the conversion bandwidth and its spectral profile are suitably controllable; and the large width of the domains and step-difference in the grating period ease device manufacture [7]. Moreover, it is possible to increase the moderate efficiency of an ASCG for quasi continuous waves (CW) with the resonance of fundamental harmonic (FH) making it possible to realize highly-efficient broadband frequency doublers in lithium niobate (LN) waveguides [8]. Considering an FH-resonant waveguide along with the designed ASCG structure, we propose that in converting the wideband quasi-continuous FH to second harmonic (SH), it is possible to increase the efficiency envelope of resonant axial modes effectively, while the conversion bandwidth remains almost the same as the non-resonant structure.

Apodized SCG for flattop bandwidth broadenning
Using quasi-phase matching by periodically changing the sign of the nonlinearity, the input and output waves

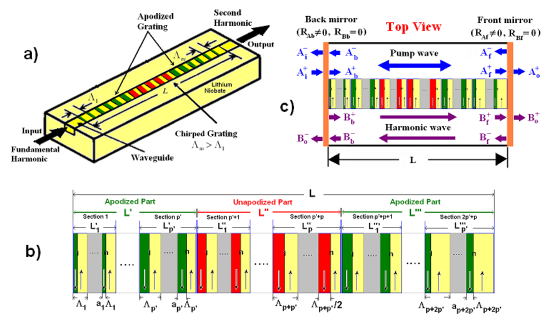

Fig. 1. Schemes of the a) device b) proposed engineered gratings and c) top view and FH resonance.

of a frequency doubler are kept in phase. However, this process requires precise temperature control and carefully fabricated gratings. Although temperature controlled and aperiodic QPM grating structures have been proposed to broaden the phase matching bandwidth, they have small conversion bandwidths. We utilize the engineering of apodized step-chirped gratings in such a way as to broaden at will the bandwidth of the frequency converter leading to a flat response with no temperature control. For the step-chirped design, the total grating length is divided into several sections of constant period but each with a slightly different period using a step-difference in period between the adjacent sections. Here, we design it with 350 sections in which each section includes 10 periods and the step-difference in periods is around 1 nm. Next, for the apodization design, the length of the central region (in red) is composed of several sections with 1:1 duty ratios while the lengths of each of the two adjacent sides (in green) with equal sections consist of the apodized regions with symmetrically increasing and decreasing duty ratios at the input and output of the device, respectively. Here, we assume that the apodization covers ~40% of the grating's total length (L) which is about 5 cm. The sketches of such a device and the engineered grating are depicted in Fig. 1(a) and 1(b), respectively. The efficiency, defined as the power ratio of the SH to FH intensity, for the (non-resonant) unapodized and apodized devices with the same length is shown in Fig. 2. It demonstrates that using the ASCG the ripple in the efficiency curve (in black solid line) can be dramatically smoothed and flattened with the ripples being reduced to less than ±0.05 dB (see red dotted line).

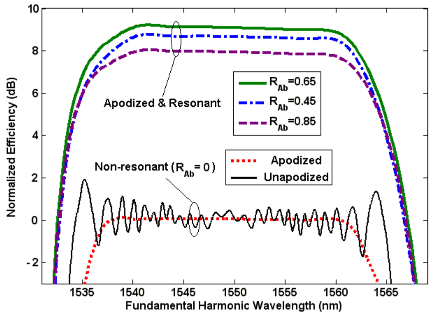

Fig. 2. Normalized efficiency vs. FH wavelength.

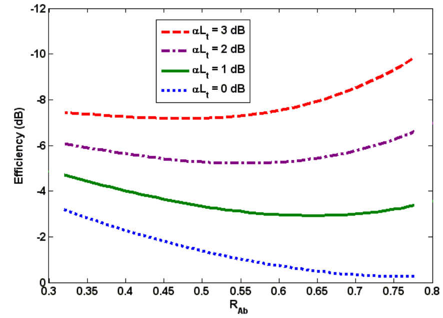

Fig. 3. Peak efficiency of the resonant ASCG vs. R_{Ab} .

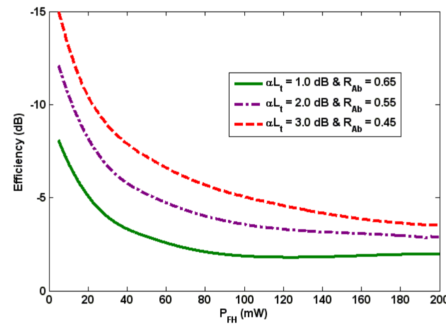

Fig. 4. Peak efficiency of the resonant ASCG vs. P_{FH}.

Resonance of FH for efficiency enhancement

An FH-resonant waveguide including ASCG as shown in Fig. 1(c) is achieved by imposing mirrors on waveguide facets in Fig. 1(a), to resonate only the quasi-CW pump. The power reflection coefficients for the FH are described by R_{Ab} and R_{Af} for the back-facet and front-facet mirror, respectively. Moreover, for an efficient resonant converter, the phase matching condition for SHG and resonance conditions for the FH wave must be satisfied simultaneously. The latter means that for a 5-cm-long structure, the resonant longitudinal mode separation is around 1.4 GHz (i.e. ~11 pm at a wavelength of ~1550 nm). Also, the linewidth depends on the photon life time and consequently the loss present in the low finesse resonator [8]. Nevertheless, to obtain a series of high-efficiency conversions of the resonant axial-modes for an FH quasi-CW shown by an envelope response, an FH-resonant waveguide in LN with an ASCG is studied and numerically characterized for different amounts of FH loss. Figure 2 also shows the normalized envelope of efficiency responses of the resonant apodized devices versus the FH wavelength for different back-facet reflectivity, R_{Ab}, and perfect front-facet reflectivity, $R_{Af} = 1$, and a total waveguide FH loss of $\alpha L = 1$ dB. With increasing R_{Ab}, the efficiency initially improves and reaches its maximum when $R_{Ab} = 0.65$ for which the impedance matching condition is satisfied. Furthermore, the 3-dB bandwidth of ~30 nm (i.e. ~3.75 THz) is obtained, which includes around 2700 axial modes with an 11.2 pm (~1.4 GHz) separation and a 1.6 pm (~0.2 GHz) FWHM linewidth and in the best case offers at least a 9-dB improvement in peak efficiency over the non-resonant device (R_{Ab} =0).

Figure 3 illustrates the maximum efficiency versus R_{Ab} for different FH loss, αL. It is clear that the highest efficiency is obtainable only for the lowest loss. Although the efficiency degrades due to loss, remarkable enhancement is still achieved at the matched condition with the proper selection of R_{Ab}. To achieve the maximum efficiency for greater FH loss, the optimum value of reflectivity can be found at lower values of R_{Ab}.

Figure 4 shows the dependence of the maximum efficiency on the FH input power, P_{FH} for different αL, and R_{Ab} for which the peak efficiency occurs in Fig. 3. It is apparent that with increasing power, the efficiency increases rapidly in the low pumping region but reduces in the high pumping region, as depicted in Fig. 4. This is because the pump power build-up in the resonator is disabled by pump depletion due to intense SHG interaction. It is also obvious when αL increases, the maximum efficiency is achieved at higher input FH powers but the maximum efficiency value is smaller.

Conclusion

An effective apodized step-chirped grating is proposed to broaden and flatten the frequency conversion bandwidth in QPM lithium niobate waveguides. Further, proposing an FH-resonant waveguide with an ASCG, we have found that the conversion efficiency envelope for quasi-continuous FH increases substantially with almost the same bandwidth, especially for low loss. For a ~21-dBm input FH power in a 5-cm-long resonant waveguide with 1-dB FH loss and the optimized back-facet reflectivity of 0.65, the maximum efficiency of about -1.8 dB over a bandwidth of 30 nm can be achieved. Additionally, larger bandwidth converters can be designed with different ASCG parameters.

References

1. M. Asobe, et al, IEICE Trans. on Electron. E88-C (2005) p. 335-41.
2. Z. Zheng et al, JOSA B 19 (2002) p. 839-48.
3. H. Wang, et al., Appl. Opt. 46 (2007) p. 1787-94.
4. Y. L. Lee, et al, Opt. Exp. 11 (2003) p. 2813-2819.
5. C.-Q. Xu, et al, IEEE J. Quantum Electron. 31 (1995) p. 981-7.
6. A. Tehranchi, and R. Kashyap, IEEE J. Lightwave Technol. 26 (2008) p. 343-49.
7. A. Tehranchi, and R. Kashyap, Opt. Exp. 16 (2008) p. 18970-75.
8. A. Tehranchi, and R. Kashyap, IEEE J. Quantum Electron. 45 (2009) p. 187-94.