Widely tunable mid-infrared difference frequency generation using apodized $\chi^{(2)}$ grating and its application to gas spectroscopy

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Abstract. *We have proposed a new device structure to achieve apodization in a quasi-phase-matched (QPM) wavelength converter. Widely tunable 3 μm-band difference frequency generation was realized using an apodized QPM $LiNbO_3$ waveguide. We have demonstrated the simultaneous detection of the absorption lines of CH_4 and C_2H_4 using the widely tunable source.*

Introduction

Mid-infrared light sources have attracted a lot of attention because they are useful for sensing environmental gases. A 3 μm-band light source is particularly important for sensing hydrocarbons because there is much strong absorption in this wavelength range [1] [2]. However, no practical laser source has been developed that can emit a continuous wave at room temperature. On the other hand, quasi-phase-matched (QPM) difference frequency generation (DFG) is an attractive technique for generating mid-infrared light because we can utilize well-established telecom laser diodes as pump and signal sources. Recently, we demonstrated 3 μm-band laser light generation in periodically poled $LiNbO_3$ (LN) ridge waveguides using a direct bonding technique. Direct bonding is especially suitable for generating mid-infrared light because it avoids any undesired absorption by hydroxyl and other groups [3]. We achieved a high conversion efficiency of 40 %/W by making best use of the advantages of direct bonding [4]. However, the narrow bandwidth of the current waveguide, yielded by quasi-phase matching, limits its application to a multiple-gas sensor. So there is a strong need for a broadband QPM device if we are to realize a widely tunable mid-infrared light source. In this paper, we present the basis for the apodization of a $\chi^{(2)}$ grating that yields an arbitrary degree of band broadening and a flat phase-matching response, as well as a high conversion efficiency. We use the method to obtain widely tunable high-efficiency 3 μm-band DFG in a $LiNbO_3$ ridge waveguide. Moreover, we apply the result to demonstrate multiple hydrocarbon gas detection. We detect the absorption lines of CH_4 and C_2H_4 simultaneously.

Concept of apodized QPM $LiNbO_3$ device

In a uniform QPM-grating device, we can increase the bandwidths by reducing the interaction length. This is because the bandwidth scales inversely with length. However, since the conversion efficiency scales quadratically with length, this approach leads to a marked decrease in conversion efficiency. Another common broadband device technology is the chirped $\chi^{(2)}$ grating [5]. This grating makes it possible to obtain a linear tradeoff between conversion efficiency and bandwidth. However, attempts to obtain a high conversion efficiency with a moderate bandwidth have resulted in large ripples in the tuning curve owing to interference arising from various phase-matching conditions of the grating. Apodization is widely used to suppress the ripples produced by Bragg gratings in semiconductors and fibers [6]. However, QPM structures are formed by reversing the spontaneous polarization, which has only two states, namely the up state (0°) and down state (180°). That means that, unlike a refractive index, it is

impossible for a nonlinear coefficient to have an intermediate state. Therefore, apodization has never been demonstrated in a QPM grating.

We found that it is possible to control the effective nonlinearity by changing the duty ratio [7]. And we exploited this characteristic to apodize a QPM grating. Figure 1 is a schematic of an apodized $\chi^{(2)}$ grating structure. To reduce unwanted ripples in the phase matching curve, we change the duty ratio at both ends of the device. The duty ratio in the center section is conventionally uniform. In addition, to increase the bandwidth, we invert the sign of the nonlinear coefficient aperiodically. Here, we define the duty ratio *f(z)* as the ratio of a non-inverted domain to one poling period. In this work, we employed the following duty ratio function [8]:

$$f(z) = \frac{1}{2}\tanh\left[\frac{2az}{L}\right], \qquad \frac{L}{2} \le z \le L \qquad (1)$$

$$= \frac{1}{2}\tanh\left[\frac{2a(L-z)}{L}\right], \qquad 0 \le z \le \frac{L}{2}$$

where *a* is an apodization parameter that adjusts the duty ratio variation, and *L* is the total length of the device. For the unapodized grating, *f(z)* is equal to 0.5. In addition, to increasing the bandwidth, we chirped the poling period linearly.

Widely tunable high-efficiency 3 μm-band DFG

We demonstrated 3 μm-band DFG with a large bandwidth and high conversion efficiency. We fabricated ridge waveguides by employing the direct-bonding technique [3]. We used a 3-inch z-cut non-doped $LiNbO_3$ wafer and a 3-inch z-cut $LiTaO_3$ wafer for the waveguide layer and substrate, respectively. First, we formed QPM gratings on the LN wafer and then directly bonded the two wafers together. We reduced the thickness of the waveguide layer to 11 μm by lapping and polishing. Finally, we fabricated 17 μm-wide ridge waveguides using a dicing saw. Since we did not use ion exchange or adhesives in the fabrication, there was no unwanted absorption by, for instance, hydroxyl and/or hydrocarbon groups. This makes the technique very suitable for the generation of mid-infrared light. Figure 2 shows the measured tuning curve as a function of signal wavelength. The corresponding idler wavelength is shown on the upper horizontal axis. For comparison, we have also plotted the theoretical tuning curves for apodized and linear chirped gratings.

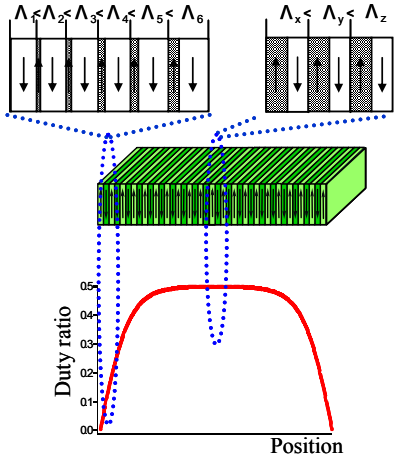

Fig. 1. Schematic of apodized grating structure

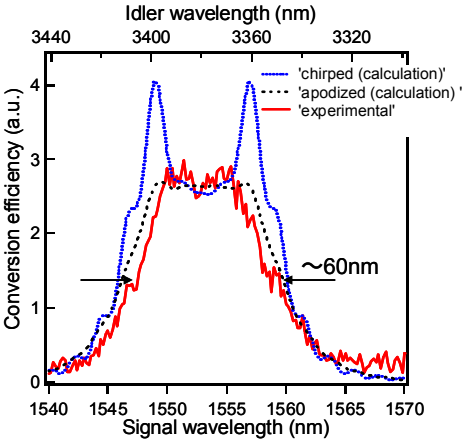

Fig. 2. Measured and calculated DFG tuning curves

The experimental and calculated tuning curves agree well. Apodization clearly suppresses the ripples in the phase-matching curve to about ±0.5 dB. The residual ripples are mainly caused by Fresnel reflection. These ripples can largely be eliminated by reducing the reflection at the end of the waveguide. We obtained a bandwidth as large as 60 nm in the 3.4 μm band and a DFG efficiency of 2 %/W. The 3 dB bandwidth for the apodized grating is 7 times larger than that of a device of the same length with a uniform grating, while the peak conversion efficiency only decreased by a factor of ~10 [4]. This technology enables us to examine the mid-IR absorption spectrum precisely over a wide range, and can be employed, for instance, in the detection of multiple gases by using a mature tunable laser diode for the 1.55 μm band.

Detection of multiple hydrocarbon gases

We demonstrated the simultaneous detection of the absorption lines of CH_4 and C_2H_4. Figure 3 shows the experimental gas detection setup. We used a 1.05 μm laser diode as a pump source. We also used a 1.55 μm band external-cavity laser diode (ECLD) and an erbium-doped fiber amplifier (EDFA) as a signal source. The pump and signal beams were combined with a fiber coupler injected into the QPM-LN WG. Pump, signal, and idler beams radiate from the QPM-LN WG output facet, and the input beams are separated from the DFG idler output beam with a dichromatic mirror. The input light was measured with a powermeter. The pump and signal powers at the output facet of the QPM-LN WG were measured and found to be approximately 600 μW and 100 mW, respectively. The DFG output beam passed through a Ge filter and was divided by a beam splitter into two parts, namely a gas-absorption detection beam and a reference beam. Both beams passed through gas cells or reference cells and were detected by a PbSe photoconductive detector. Each of the idler outputs was independently measured with the lock-in amplifier. The QPM-LN WG temperature was set at 25 °C. All the gas cells that we designed and used were made from the same fused-silica cylinder and had anhydrous silica windows, which were tilted to prevent reflection. There were two hydrocarbon gas cells and two reference cells. One cell was filled with CH_4 at 9 Torr and the other cell contained C_2H_4 at 5 Torr and buffer gas at 495 Torr. The CH_4 and C_2H_4 cells had path lengths of 20 and 10 cm, respectively.

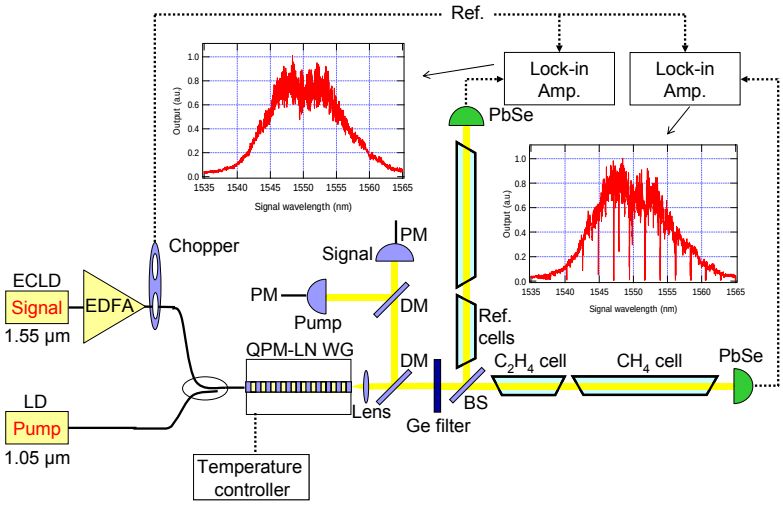

Fig. 3. Experimental setup for measuring hydrocarbon gas absorption lines

Figure 4(a) shows the absorption spectrum that resulted when CH_4 and C_2H_4 were observed simultaneously. The spectrum was provided by a single scan of the signal with a wavelength resolution of 0.01 nm/step. We obtained the absorption spectrum by dividing the transmission spectrum through the gas cells by the transmission spectrum through the reference cells, as shown in Fig. 3. Figure 4(b) shows other experimental data. A gas-absorption measurement was performed for each gas cell and the reference cell. The absorption spectrum agrees with that in the HITRAN database. We successfully demonstrated the detection of multiple gases using the broadband DFG technique.

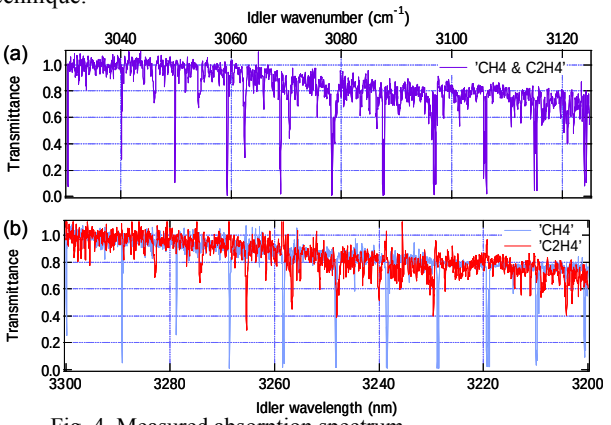

Fig. 4. Measured absorption spectrum.
(a) Simultaneously observed spectra for CH_4 and C_2H_4
(b) Superimposed individual spectra for CH_4 and C_2H_4

Conclusion

We succeeded in using apodization in a QPM wavelength converter by changing the duty ratio of a $\chi^{(2)}$ grating. This technique provides a large bandwidth and a flat phase-matching response, as well as a high conversion efficiency. We employed the technique to fabricate a DFG device based on $LiNbO_3$ waveguides. We demonstrated 3 μm-band DFG with a bandwidth of over 60 nm. These results agreed well with the theoretical predictions. We also demonstrated the simultaneous detection of the absorption lines of CH_4 and C_2H_4 and obtained a broadband absorption spectrum over 100 nm in the 3 μm region.

References

[1] Th. Toepfer, K. P. Petrov, Y. Mine, D. Jundt, R. F. Curl, and F. K. Tittel, "Room-temperature mid-infrared laser sensor for trace gas detection," Appl. Opt. vol. 36, pp. 8042-8049 ,1997.

[2] T. Yanagawa, O. Tadanaga, Y. Nishida, H. Miyazawa, K. Magari, M. Asobe, and H. Suzuki, "CH_4 monitoring in ambient air by communication band laser diode based difference frequency generation in a quasi-phase-matched $LiNbO_3$, " Appl. Phys. Lett. , vol. 89, 221115, 2006.

[3] Y. Nishida, H. Miyazawa, M. Asobe, O. Tadanaga, and H. Suzuki," A direct-bonded QPM-LN ridge waveguide with high damage resistance at room temperature," Electron. Lett., vol. 39, pp. 609-610, 2003.

[4] O. Tadanaga, T. Yanagawa, Y. Nishida, H. Miyazawa, K. Magari, M. Asobe, and H. Suzuki," Efficient 3-μm difference frequency generation using direct-bonded quasi-phase-matched $LiNbO_3$ ridge waveguides," Appl. Phys. Lett., vol. 88, 061101, 2006.

[5] T. Suhara and H. Nishihara" Theoretical analysis of waveguide second-harmonic generation phase matched with uniform and chirped gratings," IEEE J. Quantum Electron, vol. 26, pp. 1265-1276, 1990.

[6] M. M. Fejer, G. A. Magel, D. H. Jundt, and R. L. Byer, " Quasi-phase-matched second harmonic generation: Tuning and tolerances," IEEE J. Quantum Electron, vol. 28, pp. 2631-2654, 1992.

[7] R. Kashyap," Fiber Bragg Gratings," Academic Press, pp. 195-223, 1999.

[8] K. Ennser, M. N. Zervas, and R. I. Laming," Optimization of apodized linearly chirped fiber gratings for optical communications," IEEE J. Quantum Electron, vol. 34, pp. 770-778, 1998.