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# Detection of multiple hydrocarbon gases by broadband difference frequency generation using apodized $\chi^{(2)}$ grating

T. Umeki, M. Asobe, Y. Nishida, O. Tadanaga, K. Magari, T. Yanagawa and H. Suzuki
NTT Photonics Laboratories, NTT Corporation
3-1 Morinosato Wakamiya Atsugi, Kanagawa, 243-0198 Japan
Tel: +81 46 240 3218, fax: +81 46 240 4300, e-mail: umeki@aecl.ntt.co.jp

## Abstract

Absorption lines of $CH_4$ and $C_2H_6$ are detected simultaneously with a 3 μm broadband difference frequency generated in a direct-bonded quasi-phase-matched $LiNbO_3$ waveguide using an apodized $\chi^{(2)}$ grating.

## 1. Introduction

A mid-infrared light source has attracted much attention because it is useful for sensing environmental gases. A 3 μm band light source is particularly important for sensing hydrocarbons because there are many strong absorption lines 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 a periodically poled $LiNbO_3$ (LN) ridge waveguide (WG) that was made by using a direct bonding technique [3]. A direct bonded WG is especially suitable for generating mid-infrared light because it avoids any undesired absorption by hydroxyl or other groups. We achieved a high conversion efficiency of 40%/W by making the 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 as 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 demonstrate multiple hydrocarbon gas detection with a 3 μm broadband difference frequency generated using an apodized $\chi^{(2)}$ grating.

## 2. Widely tunable 3-μm-band DFG

In a uniform QPM-grating device, the bandwidths can be increased 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 results in a marked decrease in the conversion efficiency. Another commonly used broadband device technology is the chirped $\chi^{(2)}$ grating [5]. It is possible to achieve a linear tradeoff between conversion efficiency and bandwidth by using a chirped grating. However, attempts to obtain a high conversion efficiency with a moderate bandwidth have resulted in large ripples in the tuning curve due to interference arising from various phase-matching conditions of the grating. To suppress these ripples, we achieved apodization in a QPM wavelength converter by changing the duty ratio in a $\chi^{(2)}$ grating [6].

Using the apodization and direct-bonding techniques, we demonstrated a 3 μm band DFG with a large bandwidth and a high conversion efficiency. We used a 3 inch $z$-cut non-doped LN 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. We chirped the poling period linearly from 28.489 to 28.311 μm, and gradually reduced the duty ratio at both ends of the device to achieve apodization. After fabricating the QPM grating, we directly bonded the two wafers together. We then 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. The finished device was 38 mm long.

Figure 1 shows the measured tuning curve as a function of signal wavelength using a 1.064 μm pump wavelength. The corresponding idler wavelength is shown on the upper horizontal axis. The theoretical tuning curves for apodized and linear-chirped gratings are also plotted for comparison. The experimental and calculated tuning curves agree well. By using apodization, the ripple in the phase-matching curve was effectively suppressed to ±0.5 dB. A bandwidth as wide as 60 nm in the 3 μm band and a DFG efficiency of 2 %/W were obtained.

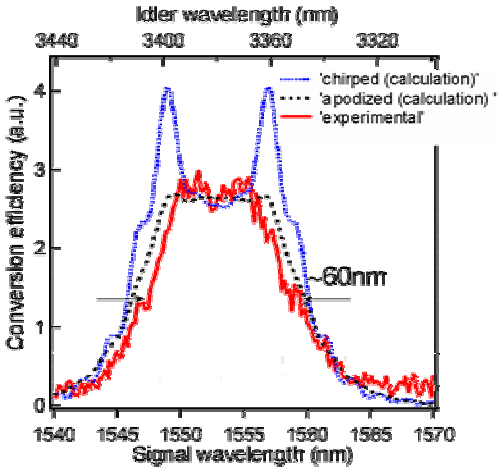


Fig. 1. Measured and calculated DFG tuning curves

## 3. Detection of multiple hydrocarbon gases

Figure 2 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.

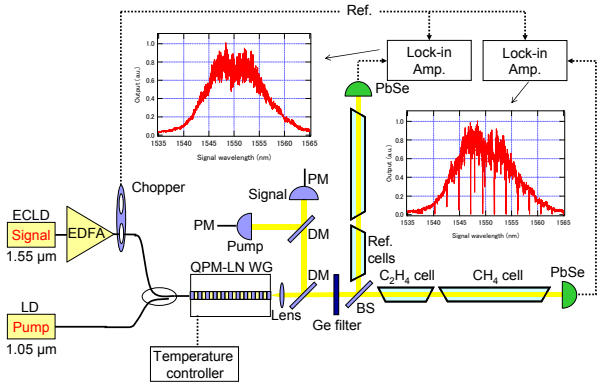


Fig. 2. Experimental setup for measuring hydrocarbon gas absorption lines

Figure 3(a) shows the absorption spectrum we obtained when $CH_4$ and $C_2H_4$ were observed simultaneously. The spectrum was obtained from 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. 2. Figure 3(b) shows other experimental data. Each gas cell and the reference cell were used in each gas-absorption measurement. The absorption spectrum agrees with that in the HITRAN database. We successfully demonstrated the detection of multiple gases using the broadband DFG technique.

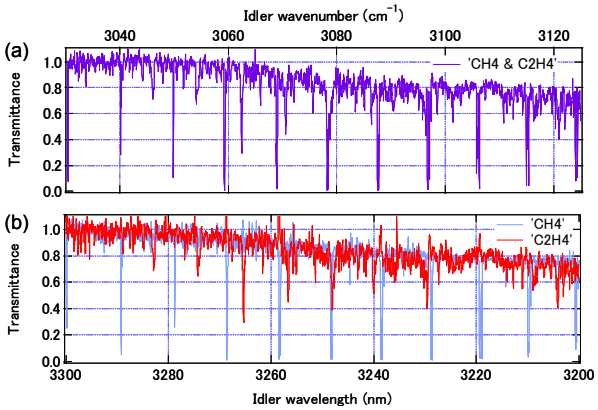


Fig. 3. Measured absorption spectrum.
(a) Simultaneously observed spectra for $CH_4$ and $C_2H_4$
(b) Superimposed individual spectra for $CH_4$ and $C_2H_4$

## 4. Conclusion

We demonstrated the simultaneous detection of the absorption lines of $CH_4$ and $C_2H_6$ with a 3 μm broadband difference frequency generated in a direct-bonded QPM $LiNbO_3$ waveguide. We obtained a broadband absorption spectrum over 100 nm in the 3 μm region by using the apodization of a $\chi^{(2)}$ grating. This technique is useful for application to a multiple-gas sensor and broadband spectroscopy experiments.

## References


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