High Quality and Efficient QPM-$LiNbO_3$ Wavelength Converter Integrated With 0.78/1.56-μm Wavelength Multiplexer

T. Umeki, O. Tadanaga, M. Asobe
NTT Photonics Laboratories, NTT Corporation
3-1 Morinosato Wakamiya Atsugi, Kanagawa, 243-0198 Japan
Tel: +81 46 240 3218, fax: +81 46 240 3259, e-mail: umeki@aecl.ntt.co.jp

Abstract

We achieved the first integration of a QPM wavelength converter with an MMI multiplexer by using a direct-bonded $LiNbO_3$ ridge waveguide. We successfully demonstrated high quality grouped wavelength conversion with a parametric gain.

1. Introduction

Efficient wavelength converters using quasi-phase -matched $LiNbO_3$ (QPM-LN) waveguide devices have a wide range of applications including as light sources for a wide variety of wavelengths (UV/Visible/Mid-IR), and as up/down converters for quantum information processing and channel converters for optical communication networks. Difference frequency generation (DFG) in a QPM-LN waveguide is being studied to prevent wavelength blocking in future photonic networks. DFG based wavelength converters have many promising properties including the simultaneous conversion of WDM channels, a large signal bandwidth, and transparency as regards modulation format [1,2].

Ti diffusion and annealed proton exchange (APE) are widely used as methods for waveguide $LiNbO_3$ fabrication. However, these methods have several drawbacks in that they can result in photorefractive damage, low stability for long-term operation and degraded nonlinearity. We have been studying direct-bonded ridge waveguide devices with a view to overcoming these problems [3]. We have developed a highly efficient DFG device using a dry etching technique and achieved highly efficient wavelength conversion based on a $\chi^{(2)}$ cascade scheme [4].

However, the $\chi^{(2)}$ cascade scheme has several issues related to signal quality. ASE noise in the pump light degrades the signal to noise ratio (SNR) of the converted signal. It is difficult to separate a pump, signal and converted signal when they are adjacent. Crosstalk induced by sum frequency generation between the pump and signal degrades the quality of the converted signal.

Recently, we reported that pumping with 0.78-μm-band light alleviates these problems, and results in a high quality converted signal [5]. The integration of a wavelength multiplexer is needed to realize a compact waveguide device for 0.78-μm-band pumping. Although the integration of a directional coupler based wavelength multiplexer has been reported for an APE waveguide [6], there has been no report of the integration of a wavelength multiplexer in a direct-bonded ridge waveguide.

In this paper, we report the first realization of a wavelength (de)multiplexer using multimode interference (MMI) on a direct-bonded QPM-LN ridge waveguide. We also succeeded in integrating a wavelength converter with a multiplexer on one chip. We demonstrated high quality grouped wavelength conversion from the C-band to the L-band with a parametric gain.

2. MMI multiplexer on direct-bonded LN waveguide

We designed a 2×1 MMI WDM multiplexer for 0.78 and 1.56 μm. MMI couplers operate based on the self-imaging effect. The theory, properties and applications of MMI devices have been well described [7]. In a homogeneous multimode waveguide with a width of W, the beat length (L_π) is defined as

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \cong \frac{4 n_g W_e^2}{3\lambda_0} \qquad (1)$$

where β_0 and β_1 are the propagation constants of the fundamental and first order modes, respectively, λ_0 is the free space wavelength, n_g is the slab effective index in the guiding region, and W_e, which is slightly larger than W, is the effective width of the fundamental mode of the multimode waveguide. An MMI coupler can perform dual-channel wavelength multiplexing when it is bar-coupled for one wavelength and cross-coupled for the other. Eq.1 shows that, for strongly confining waveguide systems, the beat length ratio ($L_\pi^{0.78}/ L_\pi^{1.56}$) is close to the ratio of the two wavelengths (1.56/0.78 μm = 2). This means that wavelength multiplexing will be obtained when $L_m= L_\pi^{0.78}= 2L_\pi^{1.56}$ where L_m is the length of the MMI waveguide. Typical values are $L_m \approx$ 3.5 mm at W = 30 μm in this study.

We prepared a 3-inch z-cut ZnO-doped LN wafer and a 3-inch z-cut $LiTaO_3$ wafer for the waveguide layer and substrate, respectively. The two wafers were directly bonded and the waveguide layer thickness was reduced to 5 μm by lapping and polishing. A ridge waveguide was then fabricated with a dry etching system.

The MMI multiplexer has two light input ports and one output port. The input and output guides are both 5 μm wide. The gap size at the junction tip between the input guides is 5 μm. A slow bend was used to provide 127-μm separation between the input access waveguide, which equals a half pitch of the fiber array. To measure the excess losses of the multiplexer, straight reference waveguides were also included on the same chip.

The multiplexing measurement was carried out by coupling 0.78- and 1.56-μm light into each port of the waveguide using a butt-coupled single-mode fiber array. A minimum excess insertion loss of 1.0/0.5 dB for 0.78/1.56 μm was achieved for a fabricated multiplexing coupler. The −1-dB bandwidth of 1.56-μm band light was about 40 nm. These results agree well with theoretical predictions.

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3. Integrated QPM wavelength converter

We integrated a QPM wavelength converter with an MMI multiplexer. A periodically poled structure with a period of 17 µm was formed in advance on ZnO-doped LN by the conventional electrical poling method. We then carried out the direct bonding and fabricated the ridge structure using the above-mentioned process. A schematic diagram of the integrated device is shown in Fig. 1. The total device length was 51 mm, the QPM section was 45 mm long and the multiplexing section was 6 mm long.

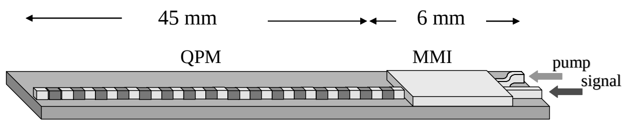

Fig. 1. Schematic view of an integrated wavelength converter with a multiplexing coupler using MMI.

We evaluated the conversion efficiency of the fabricated waveguide by measuring the SHG characteristics. We successfully obtained a peak efficiency of 1300 %/W at a wavelength of 1555.4 nm. An on-chip insertion loss of 1.5/1.0 dB for 0.78/1.56 µm was obtained for an integrated multiplexing coupler.

Then, we carried out grouped wavelength conversion based on a 0.78-µm-band pumped DFG scheme. Figure 2 shows the DFG spectrum we obtained. By employing DFG pumped with an external cavity laser diode (ECLD) at a wavelength of 777.7 nm, the grouped wavelength signals from a DFB-LD array composed of eight channels with a 100 GHz spacing were simultaneously converted from the C-band to the L-band. We defined the signal level as the signal intensity at which the pump power is 0 mW. We observed the converted signals with a converted signal to signal level difference of +1.5 dB when we launched a pump power of 130 mW into the waveguide.

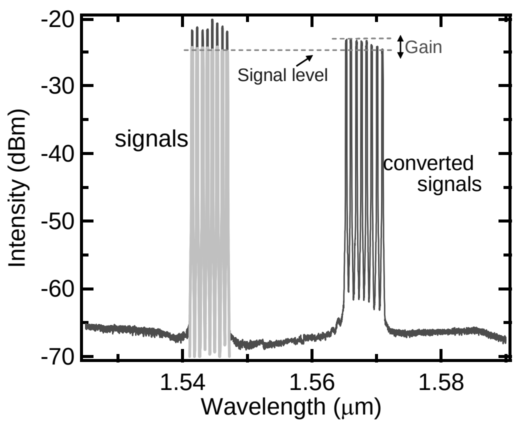

Fig. 2. DFG spectrum for grouped wavelength conversion

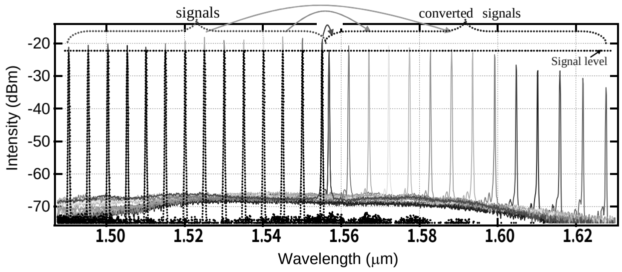

Fig. 3. DFG spectrum for a large signal bandwidth

We examined the signal bandwidth by changing the signal wavelength from 1490 to 1555.2 nm using ECLDs. Figure 3 shows the DFG spectrum at a pump power of 130 mW.

We obtained an adjacent pair consisting of a signal and a converted signal with a frequency difference of 50 GHz. In this scheme, there was no high power pump light in the 1.56-µm band so we could achieve conversion between an adjacent signal and converted signal. We also obtained a high SNR of lager than 42 dB.

We obtained a large signal bandwidth of more than 60 nm. Parametric conversion gain was demonstrated over a wide range of at least 30 nm because of the high conversion efficiency of the directly-bonded ridge waveguide.

4. Conclusion

We designed and fabricated a multiplexer using MMI on a ZnO-doped LN ridge waveguide by employing direct bonding and dry etching techniques. We obtained a low excess loss of 1.0/0.5 dB for 0.78/1.56 µm. We integrated a QPM wavelength converter with an MMI multiplexer on one chip. Grouped wavelength conversion was successfully demonstrated with a parametric conversion gain of 1.5 dB and a high SNR of lager than 42 dB. The integration of the MMI coupler/multiplexer will be useful for optical integrated circuits using ridge $LiNbO_3$ waveguides.

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