# Wavelength Conversion Laser

**Yoshiki Nishida†, Masaki Asobe, and Hiroyuki Suzuki**

**Abstract**

This paper describes a wavelength conversion laser that employs a quasi-phase-matched (QPM) $LiNbO_3$ waveguide. The QPM technique is very effective for obtaining arbitrary wavelength conversion lasers based on second-order nonlinear optical effects such as sum-frequency generation, difference-frequency generation, and second-harmonic generation. We fabricated a yellow laser based on sum-frequency generation using two laser diodes designed for telecommunication use as the pump source. The main features of this laser module are its compactness and low power consumption. It is also highly reliable since all the components meet the telecommunication reliability standard.

## 1. Introduction

A wide variety of laser diodes (LDs) has been developed for a number of industrial applications. **Figure 1** summarizes their available powers against wavelength. AlGaInP LDs, which emit red light, have been commercially used for optical disk storage [1]. A well known recent accomplishment in this field has been the development of GaN-based LDs that emit blue light in the 400-nm wavelength region. LDs developed for telecommunication use operate in the near infrared wavelength region. Of these, InP-based

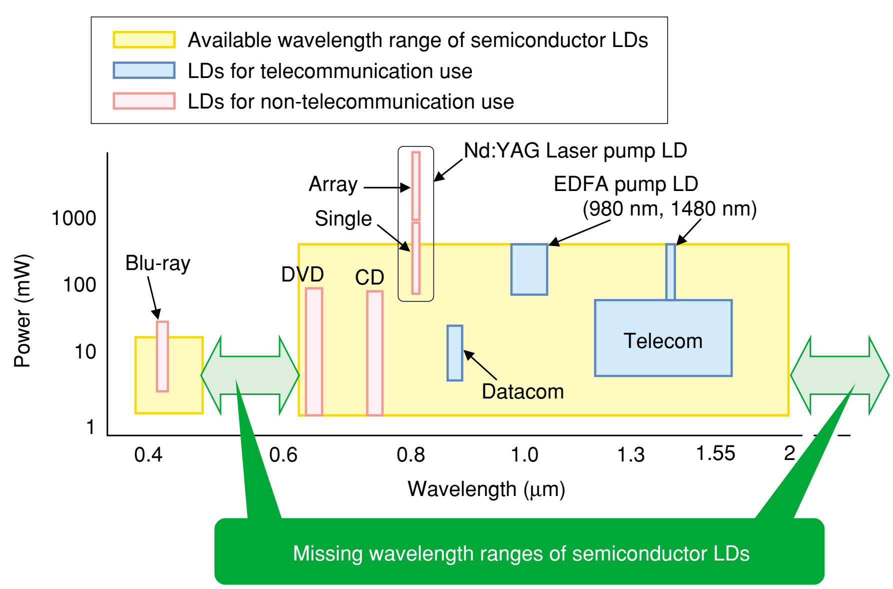


Fig. 1. Comparison of semiconductor LDs.

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1.3- and 1.5-μm LDs have been intensively developed and are widely used for practical optical fiber communication systems. Furthermore, 980- and 1480-nm LDs with a power of over 200 mW are used as pump lasers for erbium-doped fiber amplifiers (EDFA).

Although the wavelengths of commercially available LDs are limited, it may be possible to fabricate LDs in the regions colored yellow in Fig. 1 by using semiconductor materials. However, there are wavelength ranges where it is difficult to fabricate LDs using III-V semiconductor material because of the inherent energy bandgap and lattice constant of this material [2]. For this reason, LDs operating at wavelengths between 500 and 600 nm (green to yellow) and at wavelengths longer than 2 μm have not been commercialized. Although there are some gas or dye lasers and quantum cascade lasers operating in these wavelength ranges, their drawback is their large size, high power consumption, and/or low operating temperature. In particular, these lasers have a relatively short lifetime and require frequent maintenance (e.g., exchanging the gas cell or dye) to maintain their lasing performance.

In contrast, wavelength conversion techniques, especially one that uses quasi-phase matching (QPM), make it possible to fabricate lasers operating at arbitrary wavelengths [3]-[5]. Here, we describe a wavelength conversion laser that uses a QPM-$LiNbO_3$ (LN) waveguide to make a yellow laser. We also describe the principle, device fabrication, and non-telecom applications of this laser.

## 2. Principle of wavelength conversion

Wavelength conversion using QPM-LN is based on second-order nonlinear optical effects such as second-harmonic generation (SHG), sum-frequency generation (SFG), difference-frequency generation (DFG), and parametric oscillation. Of these, we used SFG to generate visible light. Sum-frequency light with a wavelength $\lambda_3 = 2\pi c/\varpi_3$ is generated by launching two input lights with wavelengths $\lambda_1 = 2\pi c/\varpi_1$ and $\lambda_2 = 2\pi c/\varpi_2$ into a nonlinear crystal. To achieve efficient wavelength conversion, which results from the interaction of the above three waves, it is essential to satisfy the phase matching condition ($\Delta\beta = 0$) in which phase mismatch $\Delta\beta$ is defined by

$$\Delta\beta = 2\pi\left(\frac{n_3}{\lambda_3} - \frac{n_2}{\lambda_2} - \frac{n_1}{\lambda_1}\right). \qquad (1)$$

In this equation, $n_1$, $n_2$, and $n_3$ are the refractive indices at the respective wavelengths $\lambda_1$, $\lambda_2$, and $\lambda_3$. QPM alleviates the phase matching constraint and allows the wavelength conversion of arbitrary wavelength combinations in the wavelength region where the material is transparent. With this technique, phase matching is achieved by fabricating a periodically poled structure whose spontaneous polarizations are reversed 180° with a period $\Lambda$ with respect to the light propagation direction in the nonlinear crystal. We can achieve conversion between various wavelengths simply by changing the poling period. The structure of a QPM-LN device is shown schematically in **Fig. 2**. Efficient wavelength conversion is achieved by satisfying the phase matching condition ($\Delta\beta = 0$) in which the phase matching difference $\Delta\beta$ is defined by

$$\Delta\beta = 2\pi\left(\frac{n_3}{\lambda_3} - \frac{n_2}{\lambda_2} - \frac{n_1}{\lambda_1} - \frac{1}{\Lambda}\right). \qquad (2)$$

On the basis of a small signal approximation, where the attenuation of the two input lights power $P_1$ and $P_2$ is negligible, the power of the converted light $P_3$

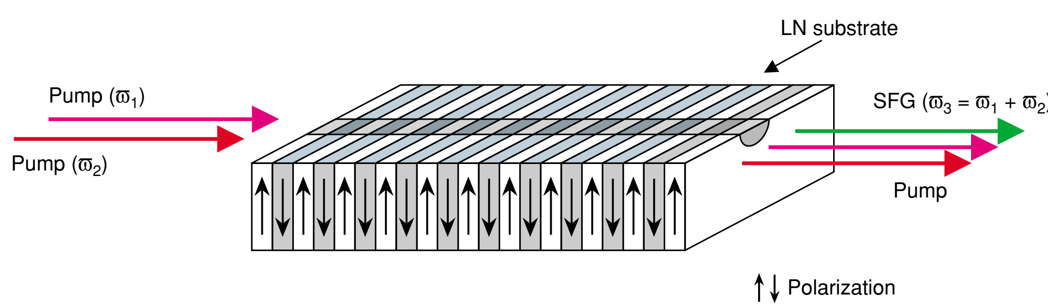


Fig. 2. Structure of QPM-LN device.

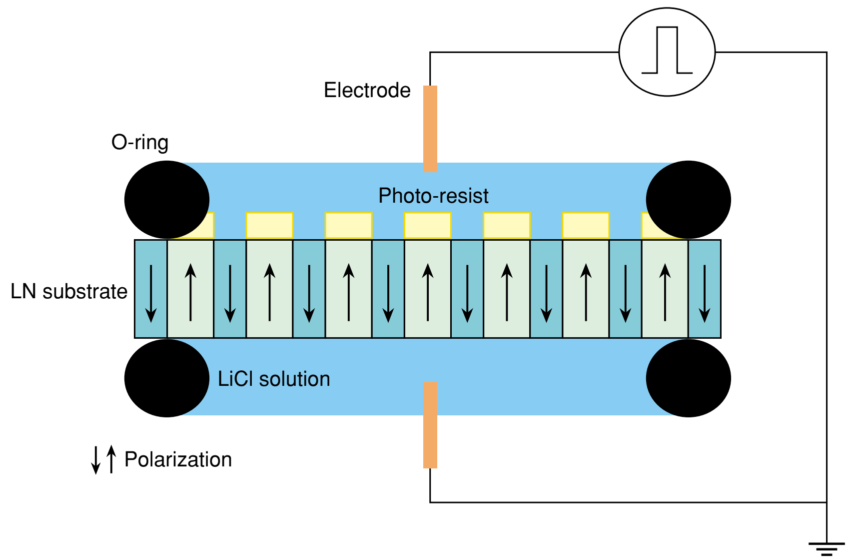


Fig. 3. Electrical poling method.

with a device length $L$ is given by Eq. (3), where $\eta$ (%/$Wcm^2$) represents the conversion efficiency per unit length and is given by Eq. (4).

$$P_3 = \frac{\eta L^2 P_1 P_2}{100} \tag{3}$$

$$\eta = \eta_{max}\left[\frac{\sin(\Delta\beta L/2)}{(\Delta\beta L/2)}\right]^2 \tag{4}$$

The conversion efficiency $\eta$ becomes constant ($\eta = \eta_{max}$) when the phase matching condition is satisfied. Therefore, Eq. (3) means that the power of the converted light $P_3$ improves in proportion to the input power $P_1$ and $P_2$ and to the square of the device length $L$.

## 3. Device fabrication

### 3.1 Periodically poled structure

It is essential to fabricate a periodically poled structure on an LN substrate in order to make a QPM-LN wavelength conversion laser. We used an electrical poling method [6]. The poling apparatus that we used is shown schematically in **Fig. 3**. With this method, we formed a comb-shaped photo-resist pattern whose structure is identical to the poling period on the LN substrate by employing a conventional photolithographic technique. We applied a liquid electrode consisting of LiCl solution to both sides of the LN surface while maintaining insulation between them. A high-voltage electric field was then applied to the LN substrate. This reversed the spontaneous polarization under the electrode. **Figure 4** shows a microscope photograph of a fabricated periodically poled structure. To reveal the periodically poled structure, we etched the LN surface with HF and $HNO_3$ solution. With this method, we confirmed that an arbitrary poling structure could be fabricated by changing the photolithography mask.

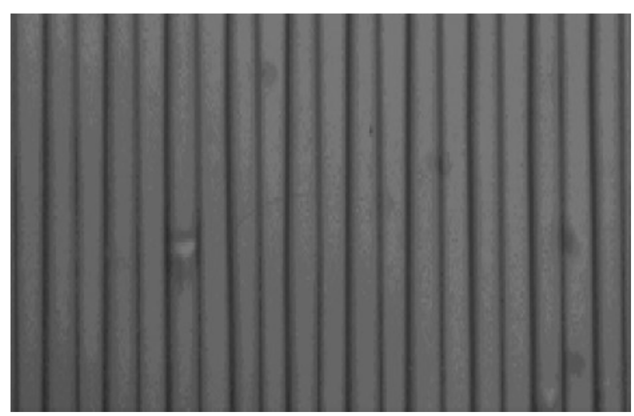

Fig. 4. Microscope photograph of periodically poled structure.

### 3.2 Direct bonding and waveguide fabrication

The waveguide structure is very effective in achieving efficient wavelength conversion. Since three interacting lights are confined to the core area there is an increase in the conversion efficiency, which is

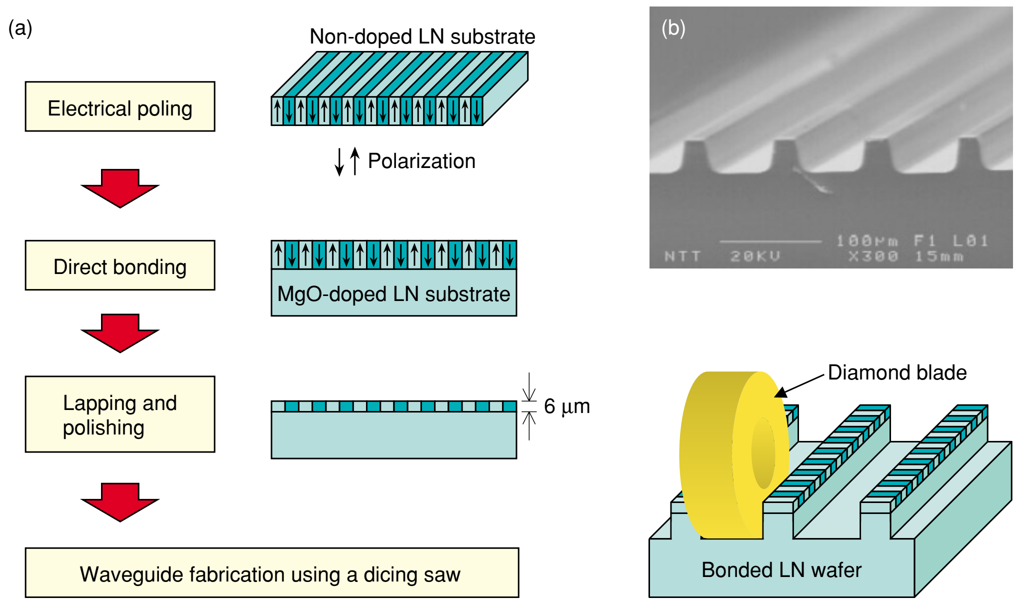


Fig. 5. Direct-bonded ridge waveguide fabrication process (a) and microscope photograph of ridge waveguide (b).

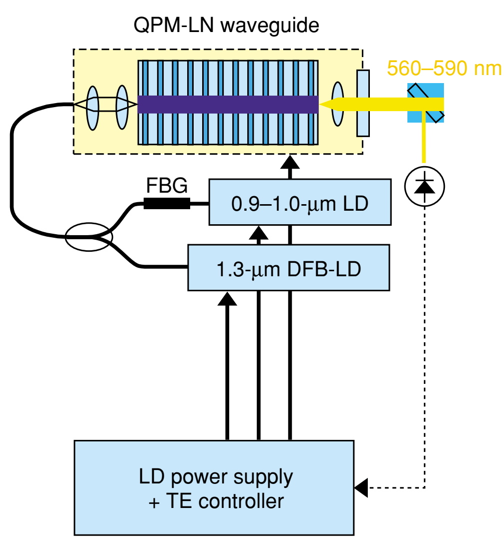


Fig. 6. Structure of the yellow laser.

inversely proportional to the interaction cross-section. We fabricated the waveguide by using the direct-bonding technique [7]. The fabrication process is summarized schematically in **Fig. 5(a)**. We prepared 3-inch LN and LT ($LiTaO_3$) substrates for the waveguide layer and substrate, respectively. A periodically poled structure was formed in advance on the LN substrate. The two wafers were brought into contact in a clean atmosphere and then annealed at 500°C to achieve complete bonding at the atomic level. The waveguide layer thickness was reduced to 6 µm by lapping and polishing. We then fabricated 8–14-µm-wide ridge waveguides by using a dicing saw. A microscope photograph of the fabricated ridge waveguides is shown in **Fig. 5(b)**. A smooth flat sidewall surface was achieved by mechanical cutting with a fine diamond blade. The fabricated waveguides were cut into pieces and then housed in a module package.

### 3.3 Structure of yellow laser

The structure of the yellow laser is shown schematically in **Fig. 6**. This laser consists of two laser diodes, a wavelength division multiplexing fiber coupler, and a QPM-LN module. To make three different yellow lasers, we prepared three QPM-LN modules with different poling periods. We used a 1.3-µm distributed feedback (DFB) LD for the first light source. The second light source was a fiber Bragg grating (FBG) stabilized 1064-nm LD, 980-nm LD, or 940-nm LD for SFG at wavelengths of 589, 560, or 543 nm, respectively. All the LDs were assembled with polarization maintaining fibers. The FBG bandwidth was set so that it was narrow enough to avoid mode partition noise. The pump lights were combined with the fiber coupler and injected into a QPM-LN waveguide through an objective lens. The packaged QPM-LN waveguide was mounted on a metal carrier and its temperature was controlled with a thermoelectric (TE) controller. A photograph of the three fabricated yellow laser modules with their power supplies is shown in **Fig. 7**. We confirmed that an SFG output of over 10 mW could be obtained with each yellow laser module. The SFG output power was stabilized by using an auto-power control system that monitors the sampled SFG output power. The laser head was 10 cm wide, 4 cm high, and 15 cm deep. The power supply was 20 cm wide, 4 cm high, and 33 cm deep. The power consumption for an SFG output power of 10 mW was 17 W. Since the laser module utilizes components that meet telecommunication reliability standards, the fabricated yellow laser should provide highly reliable long-term operation.

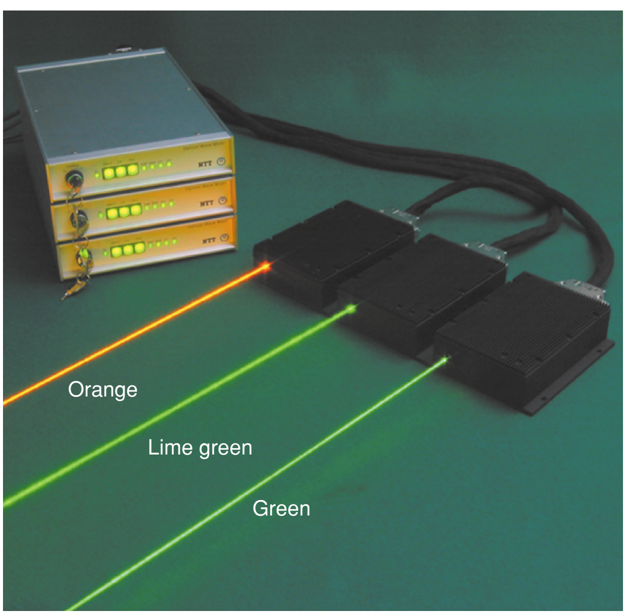


Fig. 7. Photograph of three yellow lasers with their power supplies (orange: 589 nm, lime green: 560 nm, green: 543 nm).

## 4. Wavelength conversion laser lineup

**Table 1** summarizes the characteristics of the developed wavelength conversion lasers and suitable application fields for them. A 560-nm laser is suitable for pumping a red fluorescent protein commonly used for observing living cells with a laser scanning microscope. A wavelength of 589 nm is identical to that of the sodium *D*-line, which is commonly used for measuring refractive indices $n_D$. We can expect to measure these values much more precisely if we replace the sodium lamp with a 589-nm laser. A 763-nm laser that utilizes the SHG of a 1526-nm DFB LD light is suitable for monitoring oxygen gas. Efficient combustion control achieved by monitoring the oxygen concentration in an incinerator should lead to reduced emissions of environmental pollutants such as $NO_x$ and dioxin.

In addition, mid-infrared light is suitable for environmental sensing of trace gases because there are many fundamental absorption lines in that wavelength region. Gas detection below the ppm (parts per million) level can be achieved using mid-infrared light. We have fabricated mid-infrared light lasers using QPM-LN waveguides based on DFG. By launching 980- or 1064-nm light and 1.5-µm-band light into the QPM-LN waveguide, we can obtain 2- or 3-µm-band DFG light. We are now planning to construct an environmental trace gas detection system using DFG as the mid-infrared light source in a QPM-LN waveguide.

Table 1. QPM-LN wavelength conversion laser lineup.

| Product group | Wavelength | Output power | Applications |
|---|---|---|---|
| Visible-light laser | 0.5–0.6 µm (green, lime green, yellow, orange) | 10 mW (CW) | Flow cytometer, laser scanning microscope, etc. |
| Narrow line-width laser (single-mode) | 0.65–0.9 µm (near-infrared) | 3 mW (CW) | Environmental gas sensor, etc. |
| | 2–5 µm (mid-infrared) | approx. 1 mW (CW) | |

CW: continuous wave

## 5. Conclusion

We have developed wavelength conversion lasers using QPM-LN waveguides. The QPM technique makes it possible to obtain wavelength conversion lasers at an arbitrary wavelength where the materials are transparent. We have fabricated yellow and mid-infrared light lasers based on SFG and DFG, respectively, which operate at wavelengths not covered by current semiconductor LDs. The main features of the fabricated laser module are compactness and low power consumption. They should also be highly reliable because all the components meet telecommunication reliability standards. We expect that these wavelength conversion lasers will find many industrial applications.

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