Optical DFG-based 60 GHz signal generation by using a LiTaO₃ rectangular waveguide

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Abstract: Millimeter-wave (MMW) signal generation devices using difference frequency generation (DFG) based on the second order non-linear optical effect in a rectangular waveguide were studied in detail theoretically and experimentally. The temporal and spatial coupling process of a generated MMW signal to a TE₁₀ mode in a rectangular waveguide embedded with a nonlinear crystal was analyzed using the finite-difference time-domain (FDTD) method. In the experiment, 60 GHz-band signals were successfully obtained from fabricated prototype devices using a rectangular waveguide embedded with z-cut LiTaO₃ crystal.

Keywords: rectangular waveguide, nonlinear optical effect, difference frequency generation, polarization reversal, quasi-phase matching, microwave photonics, finite-difference time-domain method

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

Millimeter-wave (MMW) and terahertz (THz) waves have been attracting much attention in many application fields: over 10 Gb/s wireless communications, high-resolution imaging, sensing, radar, and astro-physics [1, 2, 3]. Difference frequency generation (DFG) based on the second order nonlinear optical effect is a potential candidate for MMW/THz signal generation. It is possible to generate a MMW/THz signal at a desired frequency by simply adjusting the frequency difference between the two coherent lightwaves. In addition, the generated power level increases as frequency increases; the output power is proportional to the fourth power of the frequency under the same device length [4]. Therefore, DFG-based signal generation is rather attractive at higher-frequency ranges up to THz. Advanced photonic technologies developed for optical fiber communication systems (high-gain optical amplifiers, high-speed optical modulators, optical frequency shifters, optical comb generators, and sharp cut optical filters) are also applicable to control/improve DFG responses. Several studies on signal generation based on DFG have been reported [5, 6, 7]. However, there are still some challenging issues: precise control of the phase matching condition between the lightwaves and MMW/THz signals, and the coupling of the generated MMW/THz signals to other circuits.

We have proposed DFG-based devices for MMW signal generation using a rectangular waveguide embedded with a nonlinear optical crystal [4, 8]. In the proposed devices, a periodically-poled structure is utilized to obtain quasi-phase-matching (QPM) between the lightwaves and the generated MMW. The rectangular waveguide is designed to form a single-guided mode structure for the generated MMW. It only supports a TE_{10} mode in the designed operational frequency range so that the possibility of unwanted coupling of the generated signal to other modes is excluded and the distortion of the output signal by their interference is also eliminated. The resonance effect of the rectangular waveguide cavity is also utilized for enhancement of output power. By using the proposed DFG devices, signal generation from 15 to 26 GHz has been successfully demonstrated [4, 8].

In this paper, the DFG device for 60 GHz band signal generation and the theoretical and experimental studies are reported. By utilizing the finite-difference time-domain (FDTD) method, the coupling between the light-

waves and MMW and their temporal and spatial evolutions were analyzed in detail. DFG-based 60 GHz signal generation from a rectangular waveguide was also experimentally demonstrated. The frequency response of the fabricated device was in good agreement with the designed one. A T-branching waveguide device is also proposed to obtain an enhanced DFG signal over 20 dB.

2 Device structure

The basic structure of the proposed device is shown in Fig. 1(a). It consists of an MMW rectangular waveguide embedded with a z-cut LiTaO₃ crystal. In the crystal, one or a few optical waveguides are fabricated along the y-axis. For the phase matching between the lightwaves and MMW, polarization reversal structures are adopted to the LiTaO₃ crystal to compensate for phase mismatching along the propagation direction. The periodic polarization reversal period is determined by the coherence length L [4].

$$L = \frac{\pi}{|\Delta\beta|} \approx \frac{c}{2f_3(n_3^{eff} - n_g)} \quad (1)$$

where $\Delta\beta$ is the difference of the phase constants between the interacting lightwaves and the MMW, f_3 is the MMW signal frequency, n_3^{eff} is the effective index for the MMW, n_g is the lightwave group index. A SiO₂ buffer layer is inserted between the outer metal film and crystal to avoid unwanted decay of optical signals by the metal.

Fig. 1(b) shows the dispersion characteristics of the LiTaO₃ rectangular waveguides in MMW ranges. It shows that a TE₁₀ mode is only supported around 60 GHz. On the contrary, the size of the optical waveguide ($\sim 3 \times \sim 2 \mu\text{m}^2$) is rather small compared to the MMW rectangular waveguide. Therefore, it is possible to put several optical waveguides in the MMW rectangular waveguide.

The frequency response of the MMW DFG signal can be calculated by considering the QPM condition and the resonance characteristics of the MMW signal. Therefore, the frequency response of the MMW DFG signal from the designed device is obtained by considering the two frequency responses at the same time (Fig. 1(c)).

In our previous studies [4, 8], the interaction between the lightwaves and MMW signals was analyzed by use of the coupled mode theory. Therefore, the effect of the configuration of the optical waveguide in the MMW rectangular waveguide cannot be considered in detail since the effect caused by their relative configuration in the cross section was simply expressed by the coupling constant. As a result, the possibilities of MMW signal generation and its applications considering temporal and spatial domain interactions could not be discussed. In this study, we adopted the FDTD method for their detailed analysis.

Fig. 1. Structure of the proposed device (a). Dispersion characteristics of the TE_{10} mode for a MMW rectangular waveguide with different cross sections (b). Calculated frequency response of the proposed device (c).

3 FDTD analysis

In this study, we adopted the two-dimensional FDTD method based-on the Yee lattice for detailed analysis. Therefore, the dynamic behavior of the generated MMW signals and the basic operation of the proposed DFG-based device can be analyzed. The parameters used in the FDTD analysis are summarized in Table I. In the analysis, the spatial sampling point separation was set at $2\mu\text{m}$, and the temporal sampling separation was set at 0.33ps .

Typical examples of the FDTD analysis results of the MMW signal generation are shown in Fig. 2, where the detailed spatial distribution of the generated MMW signals by DFG, and their temporal evolution by propagation are plotted in Fig. 2(b)(c). We can see that the generated MMW signals spread uniformly and that the wave fronts are identified by circles [9]. Since the velocity of the lightwaves is faster than that of the MMW, Cherenkov-like field generation is obtained. By using the QPM technique, the phase mismatch between the lightwaves and MMW is compensated for, and effective MMW signal generation is obtained.

The dynamic behavior of the generated MMW signals is clearly shown, and the basic operations of the proposed DFG-based device are verified. In

Table I. Parameters of the designed device

Nonlinear optical crystal	z-cut LiTaO ₃ (congruent)
Crystal cross sectional size: $a \times b$	0.7 mm $\times$ 0.25 mm
Operational MMW frequency: f_3	60 GHz
Effective index for MMW at f_3 : n_3^{eff}	5.43
Polarization reversal period: $2L$	1.53 mm
Total device length: L_t	40.0 mm
Optical waveguide fabrication method	Annealed proton exchange
Optical waveguide core width: w	3 μ m
Optical waveguide core depth: d	2 μ m
Operational light wavelength: λ	1.55 μ m
Lightwave group index: n_g	2.17

(a)

(b)

(c)

Fig. 2. Analysis model of the proposed device (a). Calculated field distribution by use of FDTD in the proposed device at 0 mm ~ 2 mm (b), at 0 mm ~ 40 mm (c).

this calculation, the effective MMW signal sources are located at only the optical waveguide. However, the field profile of the generated MMW signal is just matched with that of the TE₁₀ mode in the rectangular waveguide through spatial and temporal evolution.

By using this FDTD analysis, the applications to the spatial and temporal correlation devices can be discussed. The details of these devices will be presented elsewhere [10].

4 Device fabrication

The DFG device was designed and fabricated by using a z-cut LiTaO₃ crystal substrate of 0.25 mm thick. The target MMW frequency was set at 60 GHz. First, the designed polarization reversal structures were fabricated in the z-cut LiTaO₃ substrate. Second, an optical waveguide was fabricated on the surface of the polarization-reversed LiTaO₃ crystal by use of the annealed proton exchange method. Next, a 0.2 μm SiO₂ buffer layer was fabricated on the surface of the crystal by using the sputtering method. After that, the 0.25 mm thick crystal was cut by use of a diamond saw to form a rectangular shape. The cross sectional area ($a \times b$) was $0.7 \times 0.25 \text{ mm}^2$. It was designed to obtain the QPM condition between the 1.55 μm lightwaves and the generated 60 GHz MMW with the length of the polarization reversal region set at $L = 0.765 \text{ mm}$. This cross sectional size also satisfies the single guided-mode condition of the rectangular waveguide around the designed frequency. The total device length (L_t) was 40.0 mm, which was designed to obtain the peak response frequency around 60 GHz. Finally, a 2 μm Al thin film was deposited on the four side walls of the crystal by use of electron beam vapor deposition.

5 Experiments

The experimental set-up for the measurement of the DFG characteristics is shown in Fig. 3(a). A 1.55 μm CW lightwave from a semiconductor laser was modulated by use of a LiNbO₃ Mach-Zehnder optical intensity modulator with a $\sim 30 \text{ GHz}$ modulation signal. By adjusting the DC bias voltage to the Mach-Zehnder intensity modulator, the lightwave carrier component was almost suppressed and two-tone optical signals with a frequency separation of $\sim 60 \text{ GHz}$ were generated. The two-tone optical signals were amplified to $\sim +20 \text{ dBm}$ by use of an Er-doped optical fiber amplifier and injected to the fabricated device. The DFG signal generated in the device was partially emitted from the end of the device to the air. Then, the emitted signal was coupled to a standard gain horn antenna (gain $\sim 20 \text{ dB}$ at 60 GHz) and measured by use of a MMW spectrum analyzer.

A typical example of the measured spectrum is shown in Fig. 3(b). Clear MMW signals were observed around the designed frequency of 60 GHz. The measured frequency response is shown in Fig. 3(c) with a theoretically calculated response. The measured peak frequency was slightly shifted ($\sim 0.5 \text{ GHz}$) to the upper side. However, the frequency separations between the subpeaks were in good agreement with the designed characteristics.

(a)

(b)

(c)

Fig. 3. Experiment set-up for the 60 GHz signal generation. The input signal was the intensity modulated optical signal with the carrier suppression condition (a). Measured spectrum of the generated signal from the fabricated device (b). Measured frequency response of the fabricated device.

6 Conclusion

In this paper, we reported on a DFG-based device for 60 GHz signal generation using a LiTaO₃-embedded rectangular waveguide. By utilizing the FDTD method, the dynamic behavior of the generated MMW signals and the basic operation of the proposed DFG-based device are clearly shown.

The DFG-based 60 GHz signal generation from the rectangular waveguide was also experimentally demonstrated. The frequency response of the MMW signals from the fabricated device was in good agreement with the designed characteristics.

Fig. 4. The structure of the proposed T-branching waveguide device (a). The photograph of the fabricated device (b).

In order to obtain signal with larger output power, we propose a new device using a T-branching rectangular waveguide and a nonlinear crystal. Its basic structure is shown in Fig. 4. By utilizing the T-branching rectangular waveguide structure, the output power level is expected to be enhanced by over 20 dB owing to the improvement in coupling efficiency.

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