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Integrated Reciprocating Optical Modulator for Optical High-Order Sideband Generation

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We demonstrated optical high-order sideband generation using a reciprocating optical modulator consisting of a pair of fiber Bragg gratings and an optical phase modulator. The reflection band of the fiber Bragg grating had a steep edge of 0.02 nm. A twelfth optical high-order sideband component was generated from a 4.4 GHZ electric signal. Millimeter waves generated as beat signals of the optical high-order sideband components were quite stable. Spectrum line widths were less than 300 Hz. The intensity modulation of the generated millimeter waves was also demonstrated by applying a baseband signal to the modulator without using another electric or optical modulator. [DOI: 10.1143/JJAP.43.579l]
KEYWORDS: optical modulation, harmonics, millimeter wave, optical filter, reflection band, reciprocating

1. Introduction

Optical high-order sideband generation has important applications in optical and wireless telecommunication networks, such as optical pulse generation for optical signal processing and millimeter wave generation for radio-on-fiber systems.[1-7] Recently, we have proposed a novel technique that enables us to obtain high-order optical sideband components effectively using a pair of optical filters placed at the optical input and output ports of an optical modulator.[8,9] By this technique, called reciprocating optical modulation (ROM), we can generate a lightwave modulated by an rf signal whose frequency is an integer multiple of an electric rf signal applied to the modulator. In ROM, some of the sideband components are fed to the optical modulator again, to effectively generate specific sideband components. The desired sideband components are taken out from the modulator, without recycling for harmonic generation. This is in contrast to mode-locked lasers and optical comb generators, where all generated sideband components are recycled into the modulators regardless of the optical frequency.[10] Thus, the desired sideband components are effectively increased, without spreading the optical power over undesired sideband components.

In this study, we demonstrate optical high-order sideband generation using a hybrid integrated reciprocating optical modulator which comprises a pair of optical filters and a $LiNbO_3$ (LN) optical modulator to suppress fluctuation. The optical filters were fiber Bragg gratings (FBGs) whose reflection bands had steep band edges less than 0.02 nm. 'TO demonstrate the stability of the ROM operation, we investigated the heterodyne beat signals of the harmonic components. A narrow-1ine-width millimeter wave of 61.6GHz was generated from a lightwave modulated by a 4.4 GHz rf-signal. Lightwave oscillation is not used in the ROM, therefore we can obtain a stable output without any complicated feedback systems that are necessary in conventional techniques for optical generation of rf signals. Also, ROM can be directly modulated by baseband signals without losing stability of the millimeter wave generation. This technique is useful for a transmitter in the radio-on-fiber system.

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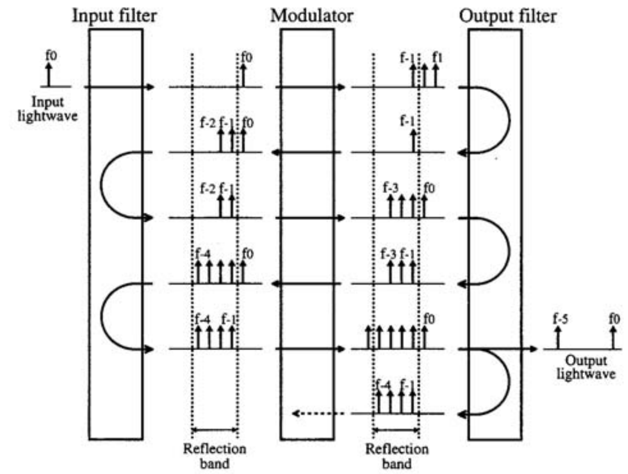

Fig.1. Principle of reciprocating optical modutator.

2. Principle of Reciprocating Optical Modulation

A reciprocating optical modulator consists of two optical filters and an optical modulator mounted between them. A schematic diagram is shown in Fig.1. A lightwave is input into the modulator through one of the filters (input filter, henceforth) and comes out from the other filter (output filter). The input filter transmits an unmodulated input lightwave from a light source, but reflects lightwaves in a specific optical frequency range. The output filter also reflects lightwaves in a specific optical frequency range, but transmits the spectrum components which we aim to generate. The unmodulated input lightwave, whose frequency is f_0, passing through the input filter is modulated by the optical modulator. The output lightwave of an optical phase modulator can be expressed by

$$\sum_{n=-\infty}^{\infty} J_n(\Delta\phi)\exp[i2\pi f_n], \quad f_n = f_0 + nf_m, \qquad (1)$$

where f_m is the frequency of the electric sinusoidal rf signal applied to the electric ports of the optical modulator. $\Delta\phi$ denotes the amplitude of the induced phase shift of the lightwave at the modulator. j_n is the first kind Bessel function of the n-th order. Considering that several components of the generated harmonics are in the reflection bands of both the input and output filters, we call these components intermediate lightwaves. The intermediate lightwaves reflected by the output filter are modulated again and reflected by the input filter. The reflected lightwaves pass through the modulator. Thus, the intermediate lightwaves are confined between the two filters, and are modulated several times by the modulator. As a result, the high-order harmonics can be effectively obtained. These two filters have two purposes. They both send the intermediate lightwaves back to the modulator. Additionally, the input filter leads the unmodulated lightwave from the light source into the modulator, while the output filter extracts the desired spectrum components. To illustrate the operation of the reciprocating optical modulation, a block diagram of fifth-order harmonic generation is shown in Fig.1. We suppose that the two filters reflect the spectrum components f_{-1} , f_{-2}, f_{-3}, f_{-4} and f_{-5}. For simplicity, the amplitude of the electric signal is assumed to be so small that eq. (1) can be approximated by

$$J_0(\Delta\phi)\exp[i2\pi f_0] + J_{+1}(\Delta\phi)\exp[i2\pi f_{+1}] + J_{-1}(\Delta\phi)\exp[i2\pi f_{-1}]. \quad (2)$$

This system operates in the following steps.

1) Upper and lower sidebands whose frequencies are f_{-1}, and f_{+1} , respectively, are produced by the modulator.

2) The lower sideband f_{-1} is reflected by the output filter.

3) The reflected lightwave is modulated again by the modulator, and spectrum components f_{-2} and f_0 are generated.

4) The input filter reflects component f_{-2}, so the modulator generates components f_{-3} and f_{-1} .

5) Spectrum component f_{-5} is produced from f_{-3} in the same way as in steps 3) and 4), and passes through the output filter.

Finally, we can obtain component f_{-5} from the output port of the output filter. Note that the modulator must be able to modulate the backward lightwave in addition to the forward lightwave, to camy out step 3). When we use filters that reflect spectrum components f_{-1} , f_{-2}, •••, $f_{-(n-1)}$, component f_{-n} can be generated through several iterations of the above steps. Each modulation step should be in phase, so that, the intensity of the spectral components depends on the difference in the optical phase of successive ROM processes. Thus, we can modulate the intensity of the millimeter wave by changing the optical phase retardation in the modulator.

3. Hybrid Integrated Reciprocating Optical Modulator

The shape of the reflection band edge of the FBG affects the performance of the ROM. When the operation frequency f_m is lower than 10GHz, the most important factor is the slope width, to take out the desired component effectively. The slope width is defined by the frequency width for the 0.5 to 3dB side slope of the FBG reflectivity spectrum. We newly designed an FBG whose slope width is narrower than 0.05nm, and the reflection band width is from 0.3nm to 0.4nm. The reflection band width is defined by the frequency width where the return loss is less than 1dB. The FBG length was fixed to be 15 mm for easy assembling. We used the apodization technique with super-Gauss functions described by

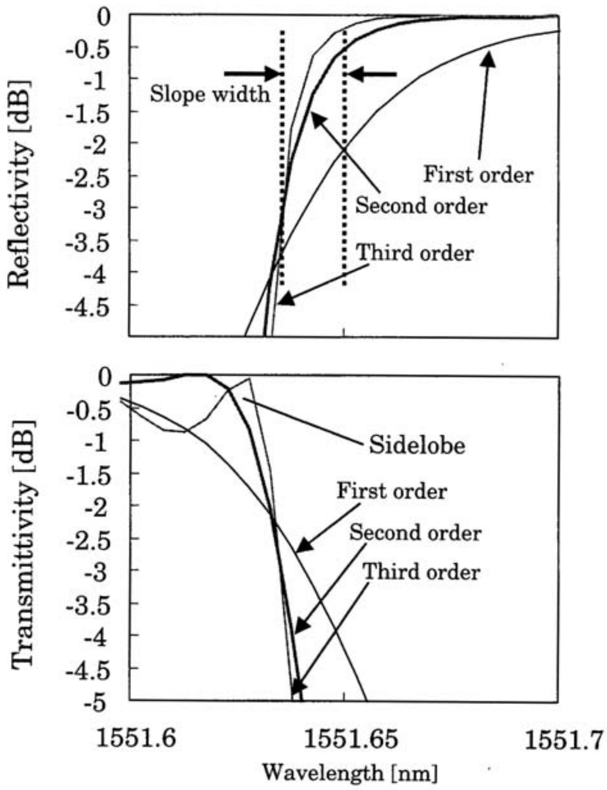

Fig.2. Numerically calculated reflection and transmission coefficients of designed FBGS using super-Gauss function apodization.

$$\exp\left[-\left(\frac{x}{A}\right)^{2n}\right], \quad (3)$$

where n is the order of the super-Gauss function. The position in the grating is expressed by x, where the point of $x = 0$ corresponds to the center of the grating and x is normalized by the size of the grating (divided by 15 mm/2). The FBGs were designed by first-, second- and third-order super-Gauss functions. Figure 2 shows the shape of the band edge. Upper and lower plots are, respectively, reflection and transmission coefficients. The parameters A were 0.3804 for n = I (first order), 0.6168 for $n = 2$ (second order), and 0.7246 for $n = 3$ (third order). The slope widths were 0.04nm for $n = 1$, 0.015nm for $n = 2$, and 0.01nm for $n = 3$. The width is a decreasing function of n, but when $n = 3$ there is an undesired sidelobe in the transmission coefficient. Thus, we used the second order super-Gauss function for the fabrication of FBGs in the ROM. Figure 3 shows reflection coefficent of a fabricated FBG. The 1dB reflecton band width was 0.38 nm (48 GHz), where the return loss increases less than I dB compared with the loss at the center wavelength of the FBG. The slope widths were less than 0.02 nm (2.5 GHz). For a reciprocating optical modulation with a high efficiency, the sideband components should not appear in the slopes, otherwise they lose their power in each refiection. In our fabricated FBGs, the minimum modulation frequency to fulfill this condition is 2.5 GHz. Without the use of such sharp FBGs, the frequency of the modulation signal fed to the ROM should be much higher.

The optical signal reciprocates between the input and output optical filters. The sideband components generated in

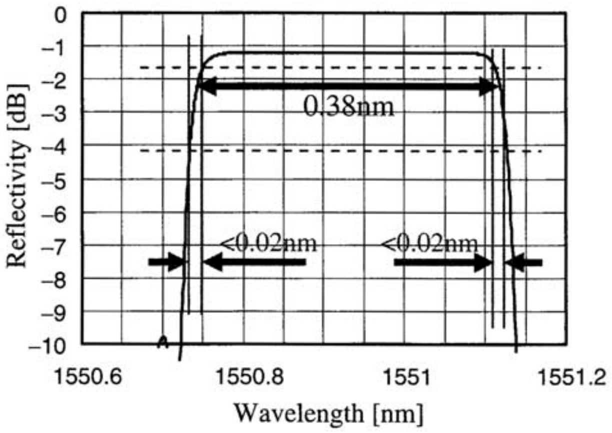

Fig. 3. Reflection coefficient of a fabricated FBG.

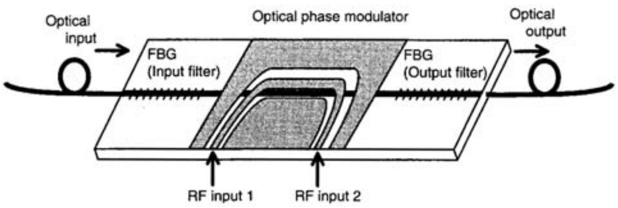

Fig. 4. Schematic structure of reciprocating optical modulator. Rf signal is fed to each electric port to obtain bidirectional modulation.

the successive modulation steps interfere with each other. The output spectrum depends on the optical path length in the modulator. Thus, the output may fluctuate due to temperature change or vibration, when we use discrete components for an ROM setup. To obtain a stable output, we fabricated a hybrid integrated reciprocating optical modulator consisting of a pair of FBGs and a $LiNbO_3$ optical phase modulator, as shown in Fig. 4. The length of the modulator was 38.0 mm. The FBGs were fixed in V-grooves on SiO_2 Substrates, and directly attached to the modulator chip .

4. Experimental Results

Figure 5 shows the experimental setup to demonstrate the generation of the optical high-order sideband components

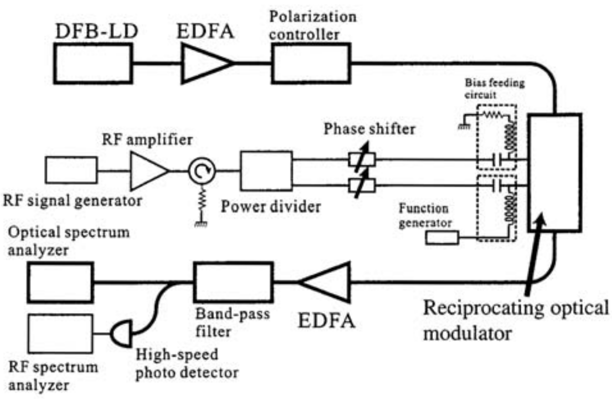

Fig. 5. Experimental setup of reciprocating optical modulator. Beat signals in millimeter band are generated using a high-speed photodetector.

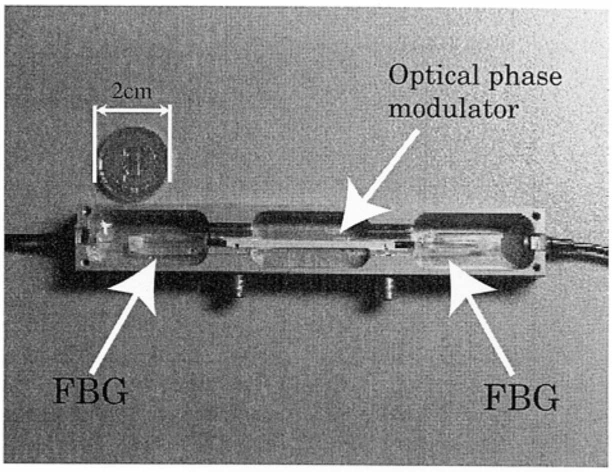

Fig. 6. Fabricated reciprocating opticat modutator.

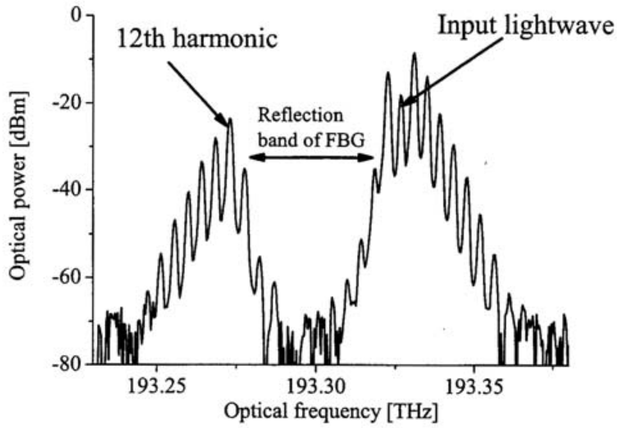

Fig. 7. Optical spectrum ot output hghtwave.

using ROM. The optical power at the input port of the modulator was 0.0 dBm. The frequency and the intensity of the rf signal fed to the modulator were 4.4GHz and 21.4 dBm, respectively. The optical frequency of the input lightwave was slightly higher than the edge of the refiection band of the FBGs. Figure 6 shows a fabricated reciprocating optical modulator. One round-trip time of the lightwave in the ROM is estimated to be approximately 452ps = $(2.2\mathrm{GHz})^{-1}$. Therefore, the rf signal is almost double the frequency of lightwave reciprocation. As shown in Fig.7, optical high-order harmonics components were effectively generated in the lower sideband, due to reciprocation of the lightwave between the optical filters. The lower sideband components of less than the 12th order were in the reflection band of the FBGs. Heterodyne beat signals of the modulated lightwaves were generated using a high-speed photodetector and measured using an rf spectrum analyzer in the millimeter band (V-band 50-75 GHz). Figure 8(a) shows the spectrum of the generated millimeter waves whose frequency was 14 times that of the rf signal. The line width was narrower than 300Hz. As shown in Fig. 8(b), we obtained stable millimeter-wave generation, although feed-back control techniques for stabilization were not used. We measured the millimeter wave power as a function of input rf frequency. The successive modulation steps in the ROM

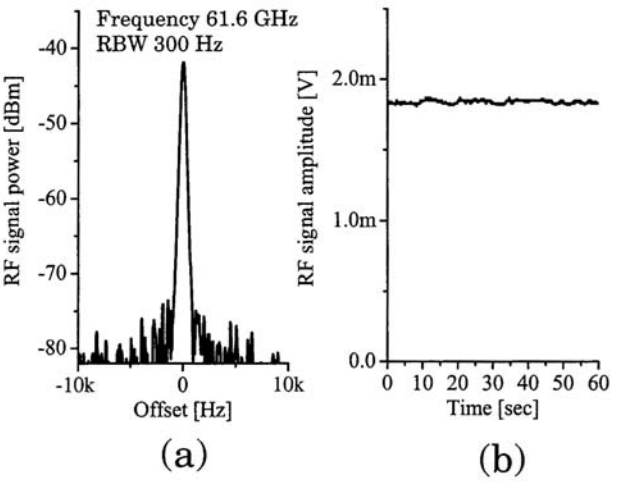

Fig. 8. Millimeter wave (61.6GHz) generated from an rf-signal of 4.4 GHz, using hybrid integrated reciprocating optical modutator. (a) Rf spectrum with a resolution bandwidth of 300 Hz. (b) Time domain profile.

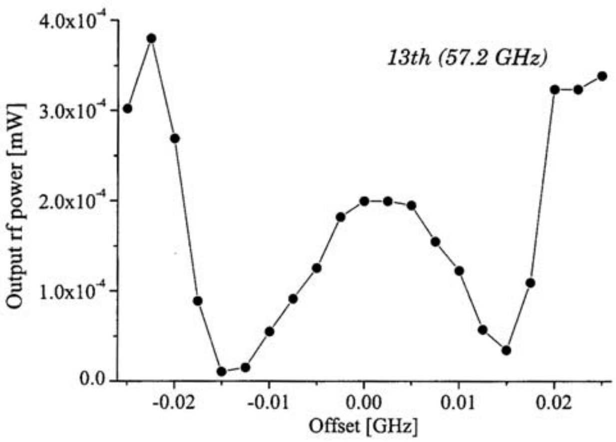

Fig. 9. Intensity of 13th order millimeter wave, as a function of input rf frequency (detuning from 4.4 GHz).

process should be in phase to obtain the effective hannonic generation, [8] so that output depends on input rf frequency, as shown in Fig. 9. The rf signal is fed to each electric port to obtain bidirectional modulation. Also, we performed intensity modulation of the millimeter waves by changing the phase retardation in the modulator. A baseband signal was applied to the modulator via the bias feeding circuit as shown in Fig. 5, by which the phase retardation can be controlled. Figure 10 shows the time domain intensity profile of the 14th-order millimeter wave. The baseband modulation signal was a 100 kHz rectangular pulse signal, whose amplitude was 2.0V, while the half-wave voltage of the phase modulator at 4.4 GHz Was 6.4V. Due to the successive modulation steps, we can switch the intensity of the rf signals by applying a small signal whose amplitude is much smaller than the half-wave voltage.

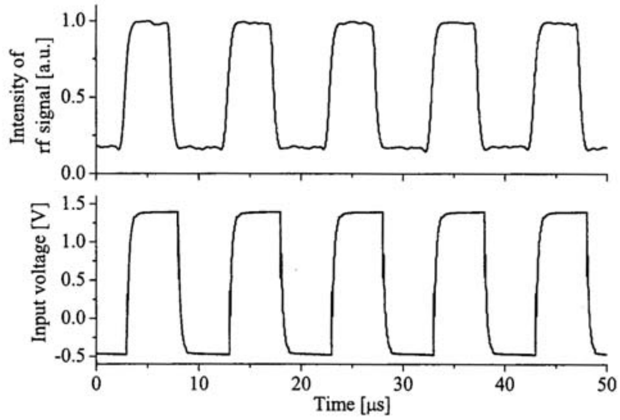

Fig. 10. Intensity modulation of 14th-order millimeter wave (61.4GHz) by a baseband signal (100 kHZ rectangular pulse trains).

5. Conclusion

We demonstrated the generation of optical high-order sideband components and millimeter waves, using a hybrid reciprocating optical modulator consisting of a pair of FBGs and an optical phase modulator. A 61.6GHz millimeter wave was obtained from a 4.4 GHz signal. The line width of the millimeter wave was smaller than 300 Hz. The intensity was also stable, without using stabilization feedback control. We also demonstrated the intensity modulation of the generated millimeter wave by applying a baseband signal to the modulator without using anotherf electric or optical modulator. The intensity of the millimeter wave can be controlled by a signal whose amplitude is much smaller than the half-wave voltage of the modulator.

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