Reciprocating Optical Modulation for Millimeter-Wave Generation by Using a Dual-Section Fiber Bragg Grating

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Abstract − **We investigated reciprocating optical modulation (ROM) for millimeter-wave generation. The system was composed of an optical phase modulator and a pair of optical filters. A lightwave modulated by V-band millimeter waves was obtained from a 5-GHz electric signal. The spectrum linewidths of the generated 60-GHz millimeter wave was smaller than 300 Hz. By using mode-coupling equations, the spectra of output lightwave were theoretically calculated. It was shown that the spectra depend on the optical path length between the two optical filters, so that harmonic generation and mixing with baseband signals can be obtained simultaneously. Intensity modulation of the generated millimeter wave was demonstrated by applying a baseband signal to the modulator without using another electric or optical modulator.**

Index Terms − **Filter, millimeter wave, optical modulation, reciprocating.**

I. INTRODUCTION

OPTICAL MODULATION in the millimeter wave, or microwave band, is a key technology for radio-on-fiber systems [1]. Traveling-wave optical modulators are often used to obtain broad-band optical response up to the millimeter-wave region [2]. Resonant-type modulators can also be used to obtain effective optical modulation in a particular band [3], [4]. However, because the modulation efficiency at a high frequency is very small, large-amplitude electric signals must be applied to the optical modulator. Recently, we proposed a novel technique that enables obtaining high-order optical harmonics effectively by using two optical filters placed at the optical input and output ports of an optical modulator [5].

By using this technique, called reciprocating optical modulation (ROM), we can generate a lightwave modulated by a radio frequency (RF) signal whose frequency is an integer multiple of that of an electric RF signal applied to the modulator. Thus, we can reduce the frequency of the electric signal in circuits driving 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-lock lasers and optical comb generators, where all generated sideband components are recycled into the modulators regardless of the optical frequency [6]. Thus, the desired sideband components are effectively enhanced without spreading the optical power over undesired sideband components. Because the difference between optical frequencies of generated sideband components corresponds to the millimeter-wave band, we can generate a millimeter wave by feeding the output lightwave to a high-speed photo detector. In addition, the intensity of the millimeter wave can be modulated by feeding a baseband signal to the optical modulator. Thus, we can perform optical subcarrier generation and baseband modulation simultaneously through the use of an optical modulator and two optical filters, without using any electrical mixing devices or another optical modulator.

This paper is organized as follows. In Section II, the principle of ROM is described briefly. In Section III, we discuss generation of optical harmonic components in ROM by using mode-coupling equations . Experimental results and discussions are given in Section IV. Millimeter-wave generation was demonstrated by using a ROM setup with a dual-section fiber Bragg grating (FBG). We also demonstrated intensity modulation of the generated millimeter wave. Our conclusion is presented in Section V.

II. PRINCIPLE OF OPERATION

Our system consists of two optical filters and an optical modulator mounted between them. A schematic diagram is depicted in Fig. 1 . A lightwave is input into the modulator through one of the filters (hereafter called the "input filter") and comes out from the other filter (hereafter referred to as the "output filter"). The input filter is a narrow-band optical filter that transmits an unmodulated input lightwave frorn a light source and reflects lightwaves in a specific optical frequency range. The output filter is a band-rejection filter whose center wavelength equals the wavelength of the input lightwave. 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

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

where f_m is the frequency of the electric sinusoidal RF signal applied to 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 nth order.
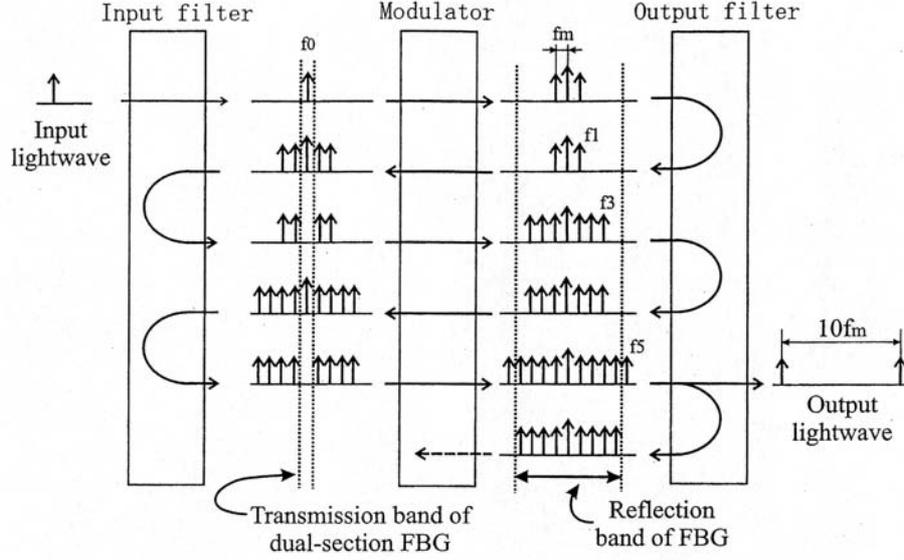
Fig. 1. The principle of ROM.

Consider that several components of the generated harmonics are in the reflection bands of both the input and the output filters, and 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 go through the modulator. Thus, the intermediate lightwaves are confined between the two filters and are modulated several times by the modulator, with the result that the high-order harmonics can be effectively obtained.

These two filters have two purposes. They both send the intermediate lightwaves back to the modulator. In addition, 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 ROM, a block diagram of the fifth-order harmonic generation is shown in Fig. I . We suppose that the output filter reflects the spectrum components f_0 , $f_{\pm 1}$, $f_{\pm 2}$, $f_{\pm 3}$, and $f_{\pm 4}$ and that the input filter reflects all spectrum components except for f_0 . For simplicity, the amplitude of the electric signal is assumed to be so small that (1) can be approximated by $J_0 (\Delta\phi) \exp[\mathrm{i}2\pi f_0] + J_1 (\Delta\phi) \exp[\mathrm{i}2\pi f_{+1}] + J_{-1} (\Delta\phi) \exp[\mathrm{i}2\pi f_{-1}]$.

This system operates in the following steps (see Fig. 1).

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

Step 2) The sidebands are reflected by the output filter.

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

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

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

We note that the modulator must be able to modulate the backward lightwave in addition to the forward lightwave in order to carry out step 3. Finally, we can obtain components f_{+5} and f_{-5} from the output port of the output filter. Thus, if we apply a 5-GHz RF signal to the modulator, the lightwave intensity modulated by a 50-GHz RF signal can be generated. When we use an output filter that reflects the spectrum components $f_0, f_{\pm 1}, \ldots, f_{\pm n}$, the component $f_{\pm(n+1)}$ can be generated through several iterations of these steps. The intensity of the spectral components depends on the difference in the optical phase in successive ROM processes. Thus, we can modulate the intensity of the millimeter wave by changing the optical phase retardation at the modulator.

III. ANALYSIS BY MODE-COUPLING EQUATIONS

We consider spectrum components coupled by the modulator whose frequencies are $f_n = f_0 + nf_m$. The spectrum components of lightwaves between the two optical filters are expressed by $2n + 1$ dimensional column vectors ($n \rightarrow \infty$)

$$
A \equiv \begin{bmatrix} \vdots \\ a_{-1} \\ a_0 \\ a_{+1} \\ \vdots \end{bmatrix} , \qquad B \equiv \begin{bmatrix} \vdots \\ b_{-1} \\ b_0 \\ b_{+1} \\ \vdots \end{bmatrix} \tag{2}
$$

where A is the spectral components of forward-traveling lightwaves, B is that of backward-traveling lightwaves, and a_n and b_n are the components whose frequency is f_n, A column vector N_0, whose components–except for the zeroth component–are zero, denotes the input lightwave. The zeroth component shows the intensity of the unmodulated input lightwave.

Output lightwave spectra of ROM were investigated by using vector-form mode-coupling equations

$$A = T^{\mathrm{I}} N_0 + R^{\mathrm{I}} M(\beta) B \qquad (3)$$

and

$$B = R^{\mathrm{II}} M(\alpha) A. \qquad (4)$$

α and β denote induced phase shifts at the modulator for the forward wave and the backward wave, respectively. A $2n + 1$ dimensional matrix M shows mode coupling due to the modulator and is defined by

$$M(\alpha) = \begin{bmatrix} \ddots & \vdots & \vdots & \vdots & \reflectbox{$\ddots$} \\ \cdots & M_{-1,-1}(\alpha) & M_{-1,0}(\alpha) & M_{-1,+1}(\alpha) & \cdots \\ \cdots & M_{0,-1}(\alpha) & M_{0,0}(\alpha) & M_{0,+1}(\alpha) & \cdots \\ \cdots & M_{+1,-1}(\alpha) & M_{+1,0}(\alpha) & M_{+1,+1}(\alpha) & \cdots \\ \reflectbox{$\ddots$} & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \qquad (5)$$

where $M_{i,j}(\alpha) \equiv J_{(i-j)}(\alpha)$. Matrices R^N and T^N ($N =$ I or II) are defined by

$$R^N = \begin{bmatrix} \ddots & 0 & 0 & 0 & 0 \\ 0 & r^N_{-1} & 0 & 0 & 0 \\ 0 & 0 & r^N_0 & 0 & 0 \\ 0 & 0 & 0 & r^N_{+1} & 0 \\ 0 & 0 & 0 & 0 & \ddots \end{bmatrix} \qquad (6)$$

$$T^N = \begin{bmatrix} \ddots & 0 & 0 & 0 & 0 \\ 0 & t^N_{-1} & 0 & 0 & 0 \\ 0 & 0 & t^N_0 & 0 & 0 \\ 0 & 0 & 0 & t^N_{+1} & 0 \\ 0 & 0 & 0 & 0 & \ddots \end{bmatrix} \qquad (7)$$

where the diagonal components show reflection and transmission coefficients of each spectral component. The coefficients r^N_i and t^N_i, which include phase delay and loss due to propagation between the modulator and the filters, are defined by

$$r^{\mathrm{I}}_n \equiv R^{\mathrm{I}}(f_n) \exp[-i2\pi f_n \cdot 2L^{\mathrm{I}}/v]/K \qquad (8)$$

$$t^{\mathrm{I}}_n \equiv T^{\mathrm{I}}(f_n) \exp[-i2\pi f_n \cdot L^{\mathrm{I}}/v]/K \qquad (9)$$

$$r^{\mathrm{II}}_n \equiv R^{\mathrm{II}}(f_n) \exp[-i2\pi f_n \cdot 2L^{\mathrm{II}}/v]/K \qquad (10)$$

$$t^{\mathrm{II}}_n \equiv T^{\mathrm{II}}(f_n) \exp[-i2\pi f_n \cdot L^{\mathrm{II}}/v]/K \qquad (11)$$

where $R^{\mathrm{I}}(f)$, $T^{\mathrm{I}}(f)$, $R^{\mathrm{II}}(f)$, and $T^{\mathrm{II}}(f)$ are the reflection and the transmission coefficients as functions of optical frequency. L^{I} is the optical path length between the modulator and the input filter. L^{II} is that between the modulator and the output filter. The velocity of the lightwave traveling between the filters is denoted by v. K is optical loss at the modulator. From (3) and (4), we can obtain an explicit form of A

$$A = [I - R^{\mathrm{I}} M(\beta) R^{\mathrm{II}} M(\alpha)]^{-1} T^{\mathrm{I}} N_0 \qquad (12)$$
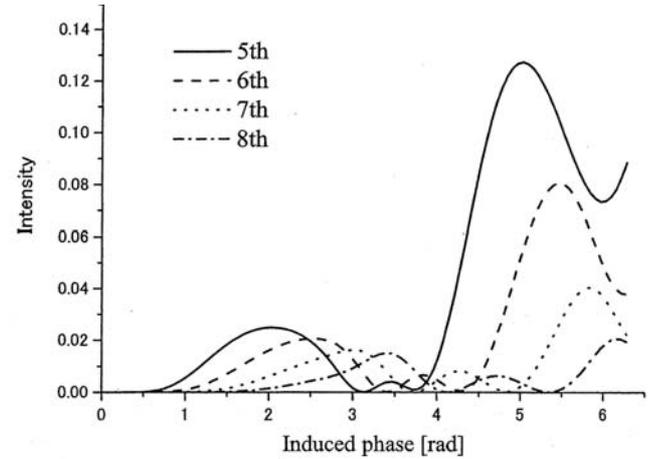

Fig. 2. Harmonic components in output lightwave calculated by mode-coupling equations as functions of amplitude of induced phase.
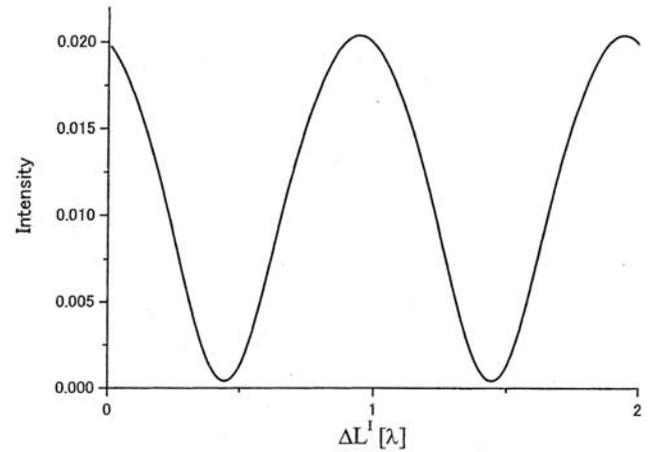

Fig. 3. Fifth-order component in output lightwave calculated by mode-coupling equations as a function of the path length between the input filter and the modulator, where ($\Delta L^{\mathrm{I}} \equiv L^{\mathrm{I}} - 1.0$ m). The unit of the x axis is the wavelength of the input lightwave in optical fibers. Induced phase $\alpha = \beta = \pi/2$.

where I is an unit matrix. Finally, we get the spectral components of the output lightwave C

$$C = T^{\mathrm{II}} M(\alpha)[I - R^{\mathrm{I}} M(\beta) R^{\mathrm{II}} M(\alpha)]^{-1} T^{\mathrm{I}} N_0. \qquad (13)$$

By using this equation, we can obtain the spectrum of the output lightwave as functions of the induced phase, the length of the optical path, and so on. In the case of $\alpha = \beta$, the intensities of fifth-, sixth-, seventh-, and eighth-order spectral components were calculated as functions of the amplitude of the induced phases, where we assumed that $L^{\mathrm{I}} = L^{\mathrm{II}} = 1.0$ m and that $K = 2.0$ dB. For numerical calculations, we considered the harmonic components up to fortieth order, and the intensities were normalized by the input optical power. The reflection coefficients of the filters are assumed to be $R^{\mathrm{I}}(f_n) = 1$ ($n \neq 0$), $R^{\mathrm{I}}(f_0) = 0$, $R^{\mathrm{II}}(f_n) = 1$ ($|n| < 5$), and $R^{\mathrm{I}}(f_n) = 0$ ($|n| \geq 5$). We neglected loss and phase delay in the filters so that $T^N(f_n) = 1 - R^N(f_n)$.
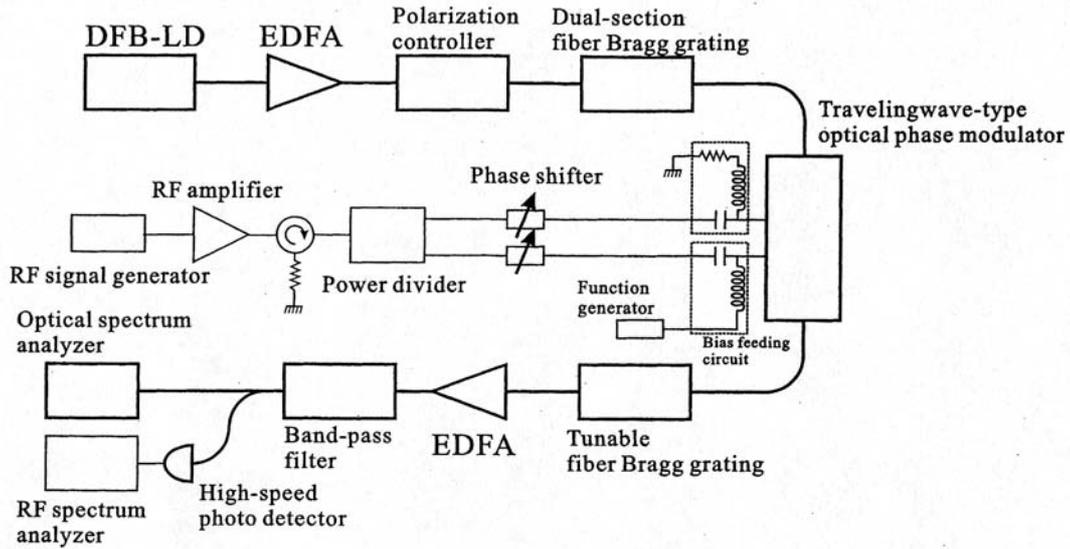
Fig. 4. Experimental setup.

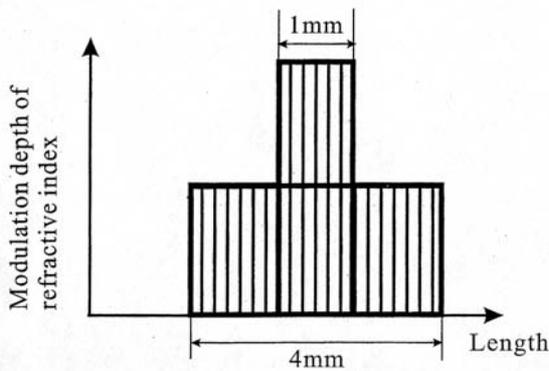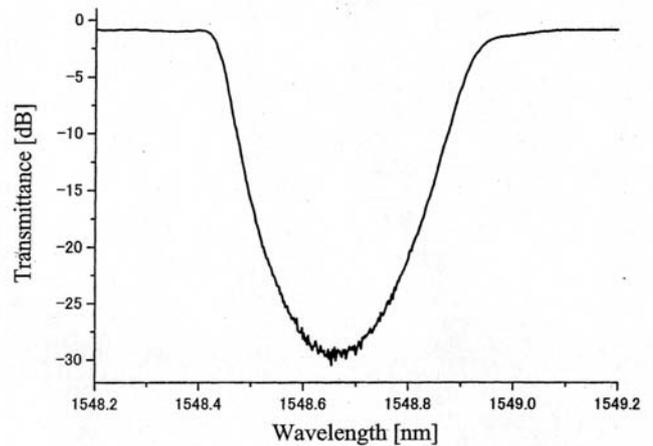Fig. 5. Refractive index profile of dual-section FBG.

Fig. 7. Transmission coefficient of output filter.

ath length, where the period is nearly equal to the input wavelength. Thus, if we change the path length, for example by applying voltage to the phase modulator, the spectral components in the output lightwave can be intensity modulated.

IV. EXPERIMENTAL SETUP AND RESULTS

Fig. 4 shows the experimental setup of our ROM system to demonstrate the generation of the millimeter wave. A traveling-wave optical phase modulator was placed between an input and an output filter. The input filter was a dual-section FBG (Advanced Optics Solutions FP-sensor FBG SN 02070141), consisting of two sections of FBGs whose properties were almost the same.

The reflection spectrum profile, which is similar to that of a Fabry-Perot filter, has very narrow (approximately 0.016 nm) transmission bands in the reflection band of one section. To obtain a free spectral range of 0.40 nm, the separation between the centers of the sections should be 3 mm, which is smaller than the length of one section, so that the sections overlap each
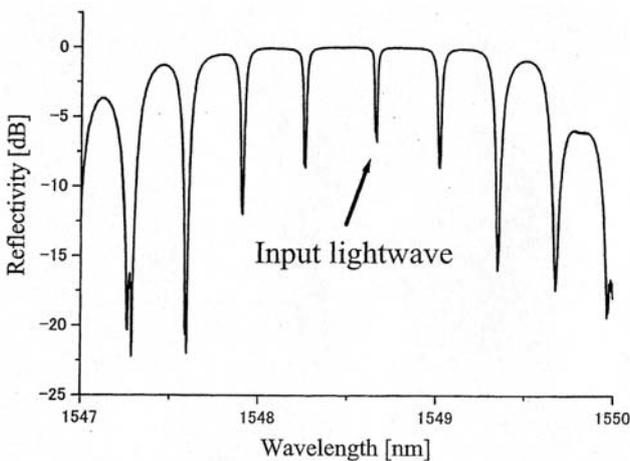

Fig. 6. Reflection coefficient of input filter.

As shown in Fig. 2, when the induced phase is approximately 2.0 or 5.0, we can generate fifth-order components effectively. Fig. 3 shows the intensity of fifth-order component as a function of L^1. The output intensity periodically depends on the optical
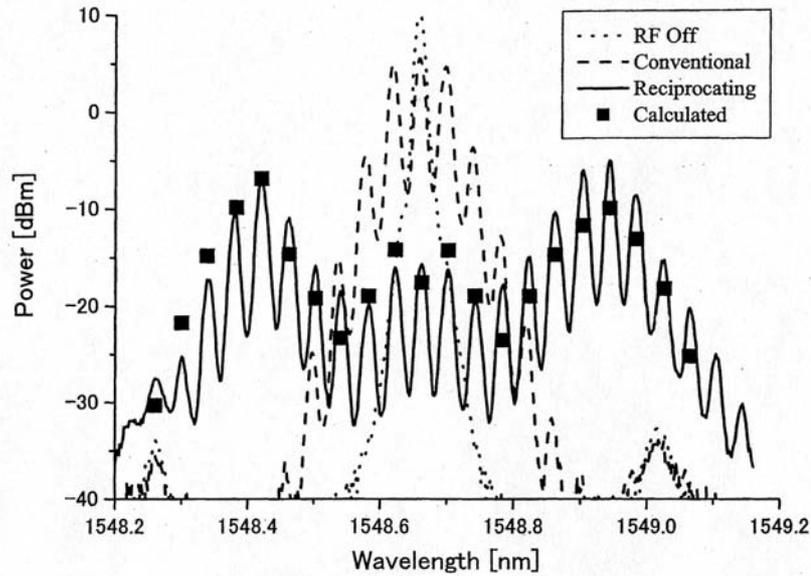
Fig. 8. Optical spectra of output lightwaves. Solid lines and dashed lines denote spectra generated by ROM and those generated by conventional optical phase modulation, respectively. In conventional modulation, the reflection band of the output filter is tuned to let all harmonic components out of the band. Dotted lines show unmodulated lightwave spectrum at the output port of the output filter, obtained by turning off the RF signal. The output filter is the same as in conventional modulation. The phases of RF electric signal and lightwave are adjusted to maximize the generated millimeter wave. The square dots show a spectrum obtained by the mode-coupling equation.
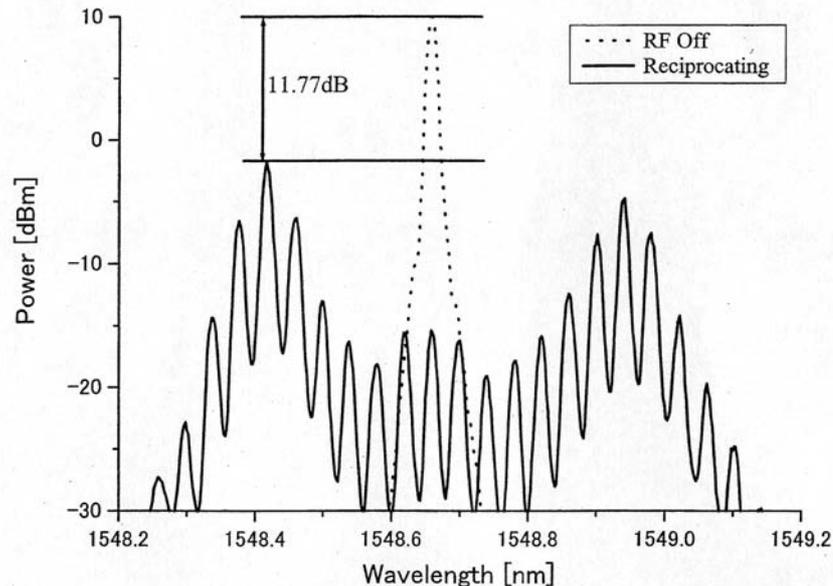

Fig. 9. Optical spectra of output lightwaves. Solid lines denote spectrum generated by ROM. Dotted lines show the unmodulated lightwave spectrum at the output port of the output filter, obtained by turning off the RF signal. The phases are adjusted to maximize +sixth-order harmonic component.

other. The modulation depth of the refractive index in the FBG was twice in the overlapping area with respect to the other area, as shown in Fig. 5. By using this refractive index profile, we obtained very narrow transmission bands, as shown in Fig. 6. The output filter was a tunable FBG whose reflection bandwidth was 0.40 nm, as shown in Fig. 7.

The center wavelength of the output filter and the wavelength of the lightwave input from the light source were set to one of the narrow transmission bands of the input filter (1 548.656 nm). Sinusoidal RF electric signals with a frequency of 5.015 GHZ and

a power of 19.5 dBm were fed to both input and output electric ports of the modulator. The half-wave voltage of the modulator was 7.0 V, so that the induced phase due to RF electric signal traveling in the same direction of lightwave should be approximately 1 .3. The frequency of the RF signal should coincide with the inverse of the round-trip time between the two optical filters in order to maintain the successive modulation processes in-phase. The phase of the RF signals was trimmed by using the delay lines to eliminate the phase difference between the forward and the backward modulation processes.
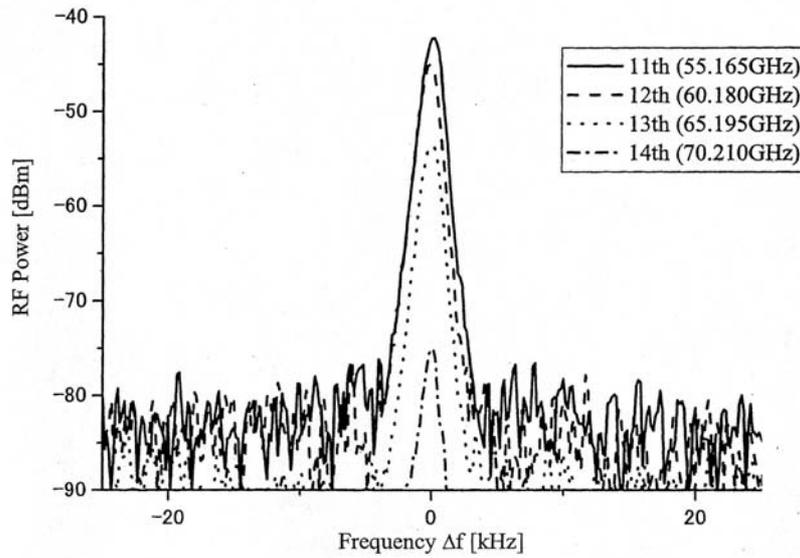
Fig. 10. Spectra of the generated millimeter wave, where resolution bandwidth of the spectrum analyzer was 1 kHz.
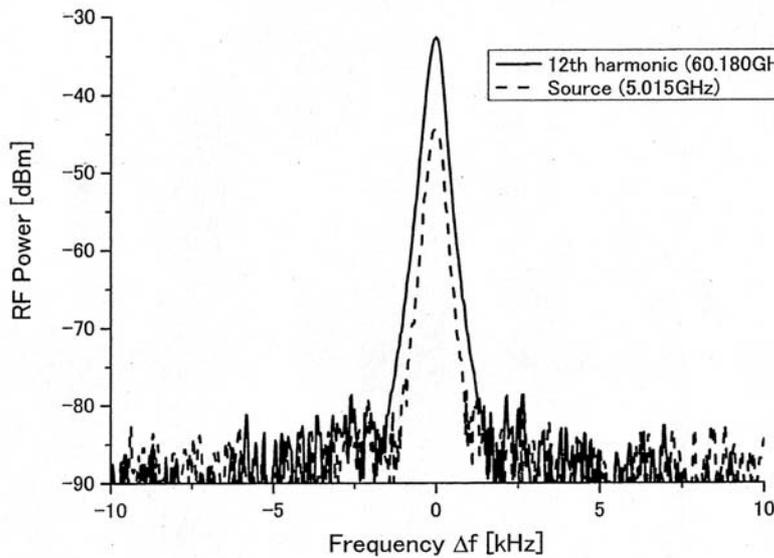

Fig. 11. Spectra of the generated millimeter wave (twelfth-order) and RF source, where resolution bandwidth of the spectrum analyzer was 300 Hz.

Fig. 8 shows the spectra of the output lightwave. The induced phase at the modulator, which can be obtained from the intensity of the f_0 component in conventional modulation, was 1.76. Thus, the induced phase due to RF signal traveling in the opposite direction of lightwave was estimated to be 0.46. Optical insertion and return losses at the modulator were 2.0 dB and 47.4 dB, respectively.

We found that, while in the spectrum generated by the conventional modulation method, there were no harmonic components higher than those of fourth order; in the spectrum generated by ROM, there were high-order harmonic components, especially those of the sixth order. The spectrum calculated by (13) was also plotted in Fig. 8. For numerical calculation, we used the reflection coefficients shown in Fig. 7 and the induced phase obtained frorn the spectrum of the conventional modula-

tion. Loss at the filters was assumed to be 3.0 dB. The return loss of the total system, which is the ratio of the forward and backward waves at the input port of the input filter, was 14.6 dB in the numerical results.

As shown in Fig. 9, effective optical wavelength conversion was achieved by using ROM. The conversion loss is 11.77 dB. We note that there is phase difference between the lower and upper sidebands due to time delay during the reciprocating process, so that the output spectra are not symmetric. Fig. 10 shows the spectra of the generated millimeter waves whose frequencies were 11, 12, 13, and 14 times that of the RF signal source (eleventh-, twelfth-, thirteenth-, and fourteenth-order RF signal, henceforth). We also measured the spectrum linewidths of the millimeter wave of the twelfth-order RF signal (60. 180 GHz) and the source RF signal fed to the mod-
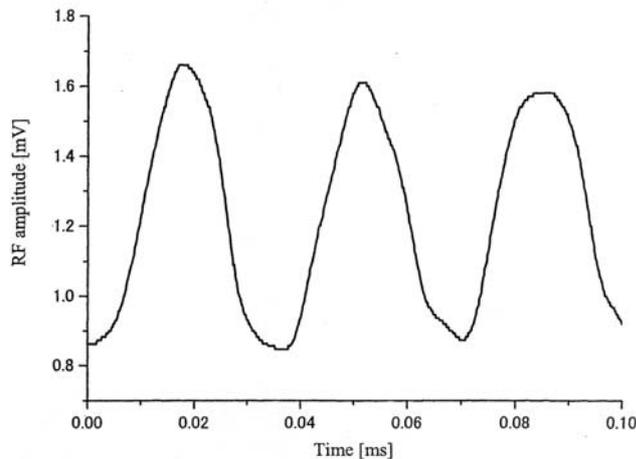
Fig. 12.   Intensity of the twelfth-order RF signal modulated by a baseband signal with a frequency of 30 kHz and an root mean square (rms) amplitude of 1.12 V.

ulator with the resolution bandwidth of 300 Hz (see Fig. 11). The linewidth was smaller than the resolution and was expected to be less than 300 Hz.

In addition, we performed intensity modulation of the millimeter waves by applying a baseband signal to the optical phase modulator via a bias feeding circuit, as shown in Fig. 4. Although only one optical phase modulator was used in our ROM system, we achieved modulation by a millimeter wave and by a baseband signal simultaneously, as shown in Fig. 12. By using optical harmonic up-converting techniques, which were previously reported [7], [8], we can also obtain subcarrier generation and baseband modulation. However, the major spectral components correspond to the fundamental or the second-order harmonic of the RF signal fed to the modulator. Thus, in order to obtain high-order harmonic components, it is necessary to increase the optical power at the photo detector, or increase the frequency and power of the RF signal. As a result, the effirciency of the harmonic generation was limited by the maximum allowable optical input of the detector and the modulation effrciency at high-frequency. On the other hand, the major spectral components generated by ROM are high-order harmonic components of the RF signal fed to the modulator, so that we can easily obtain a millimeter wave without using an electric millimeter-wave source.

We note that the response time for the baseband modulation was limited by the frequency response of the bias circuit and the round-trip time between the two optical filters. However, this can be overcome by integrating these optical and electrical components to a small monolithic device, where the round-trip time should be an integer multiple of $1/f_m$ [5]. We deduce that the response time corresponds to the time delay at the reciprocating cycle.

V. CONCLUSION

ROM with a dual FBG was investigated by using mode-coupling equations. We also demonstrated generation of millimeter waves in V band. Optical conversion loss at the modulation process was 11.77 dB for the sixth-order harmonic. The spectrum linewidths of the millimeter waves were smaller than 300 Hz. We also demonstrated intensity modulation of the millimeter wave without using any optical or electrical intensity modulators.

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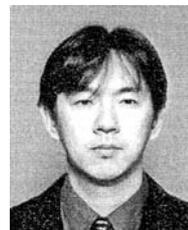
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