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60GHz帯ミリ波信号発生用往復逓倍変調器の開発

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あらまし　　2つのファイバブラッググレーティングと1つの光位相変調器からなる60GHz帯ミリ波信号発生用ハイブリッド集積型往復逓倍変調器を開発した。4.4GHzのRF信号をもとにミリ波信号で変調された光出力を安定して得ることに成功した。

キーワード　光変調、ミリ波、高調波、光フィルタ

Reciprocating Optical Modulator for 60GHz millimeter wave generation

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Abstract *We demonstrated optical generation of V-band millimetre-waves from a 4.4GHz signal, by using a hybrid reciprocating optical modulator consisting of a pair of fibre Bragg gratings and an optical phase modulator.*

Keyword Optical modulation, millimeter-wave, harmonics, optical filter

1. Introduction

Recently, we proposed a novel technique that enables obtaining high-order optical harmonics effectively by using a pair of optical filters placed at the optical input and output ports of an optical modulator [1] [2]. By using this technique, called reciprocating optical modulation (ROM), we can generate a lightwave modulated by an 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 opticai comb generators, where all generated sideband components are recycled into the modulators regardless of the optical frequency [3]. Thus, the desired sideband components are effectively enhanced, without spreading the optical power over undesired sideband components. However, when the ROM system consists of discrete components, the output fluctuates due to variation of the optical path length between the two filters.

In this contribution, we demonstrate a hybrid reciprocating optical modulator comprises a pair of optical filters and an optical modulator in order to suppress the fluctuation. Stable narrow line width miliimetre-waves of 61.6 GHz Was generated from 4.4 GHz rf-signal. The phase noise of the millimetre-wave was -74.3 dBc/Hz at 10 kHz offset. In addition, lightwave oscillation is not used in ROM, so that we can obtain stable output without any complicated feedback systems that are necessary to conventional techniques for optical generation of rf-signals.

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 Iightwave 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

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

where f_n, is the frequency of the electric sinusoidal RF signal applied to electric ports of the optical modulator. $\triangle f$ denotes the amplitude of the induced phase shift of the lightwave at the modulator. J_n is the first kind Bessel's function of n-th order. 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. Additionaily, 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 the 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

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

(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 the 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 components 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, in order to carry out step 3). When we use filters that reflect the spectrum components f_{-1}, $f_{-2}, \ldots f_{-(n-1)}$, the 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 in successive ROM processes. Thus, we can modulate the intensity of the millimetre wave by changing the optical phase retardation at the modulator.

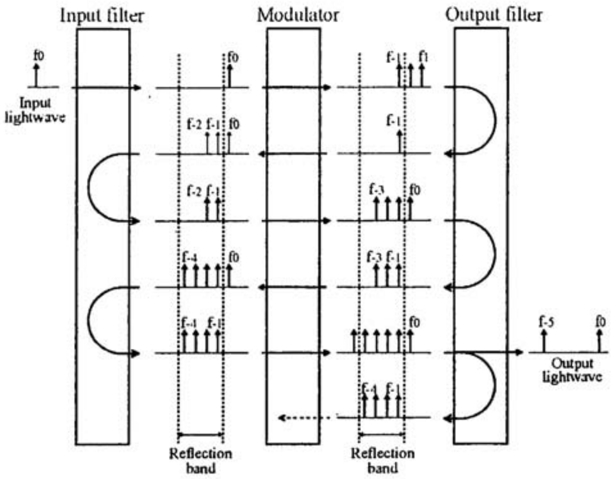

Fig.1 Principle of reciprocating optical modulation.

3. Reciprocating Optical Modulator

We fabricated a hybrid reciprocating optical modulator consisting of a pair of fibre Bragg gratings (FBGs) and a $LiNbO_3$ optical phase modulator, as shown in Fig.2. The lengths of the modulator and the FBGs were, respectively, 38.0mm and 15.0mm. The FBGs were fixed in V-grooves on SiO_2 substrates, and directly attached to the modulator chip.

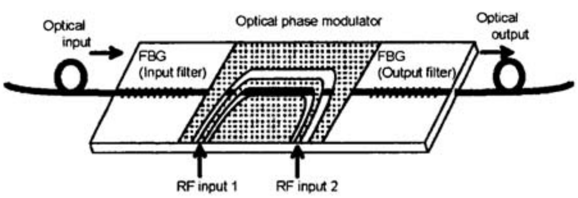

Fig.2 Schematic structure of reciprocating optical modulator. RF signal is fed to each electric port in order to get bi-directional modulation.

3. Experimental results

Fig.3 shows the experimental setup to demonstrate the generation of the optical harmonics using ROM. The optical power at the input port of the modulator was 0.0dBm. The frequency and the intensity of the rf-signal fed to the modulator were respectively 4.4 GHz and 21.4 dBm. The optical frequency of input lightwave was slightly higher than the edge of the reflection band of the FBGs.

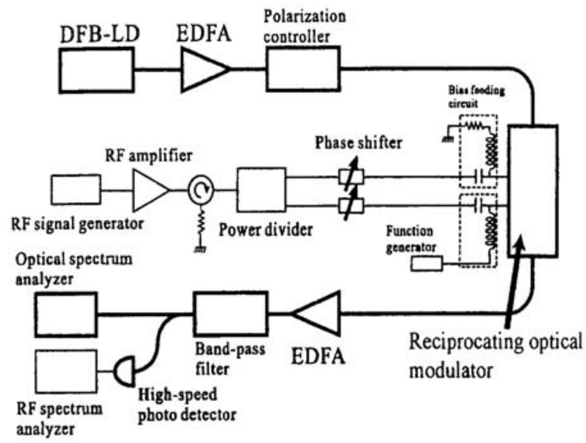

Fig. 3 Experimental setup for reciprocating optical modulation. Beat signals in millimetre band is generated by using a high-speed photo detector

As shown in Fig.4, optical high-order harmonics components were effectively generated in lower sideband, due to reciprocation of lightwave between the optical filters. The lower sideband components of lower than the 12th order were in the reflection band of the FBGs. Heterodyne beat signals of the modulated lightwaves were generated by using a highi;peed photo detector and measured by an rf spectrum analyzer in millimetre band (V-band 50-75 GHz). Fig. 5 (a) shows the spectrum of the generated millimetre waves whose frequency was 14 times that of the rf signal. The line width was narrower than 300 Hz. As shown in Fig. 5 (b), we obtained stable millimetre-wave generation, although any feedback control techniques for stabilization were not used. As shown in Fig. 6, the millimetre-wave (14th : 61.6 GHz) phase noise of ROM was smaller than that of the reference signal generated by an rf~signal source and an up-converter. We also measured the millimetre wave power as a function of the input rf frequency. The successive modulation steps in the ROM process should be in phase to get the effective harmonic generation [1], so that the output depends on the input rf frequency, as shown in Fig. 7.

In addition, we performed intensity modulation of the millimetre waves by changing the phase retardation at the modulator. A baseband signal was applied to the modulator via the bias feeding circuit shown in Fig.3, by which the phase retardation can be controlled. Fig.8 shows the time domain intensity profile of the 14th order millimetre wave. The baseband modulation signal was a 100 kHz rectangular pulse signal, whose amplitude was 2.0 V, while the halfwave voltage of the phase modulator at 4.4 GHz was 6.4 V. Due to the successive modulation steps, we can switch the intensity of the r-signals by applying a small signal whose amplitude is much smaller than the halfwave voltage.

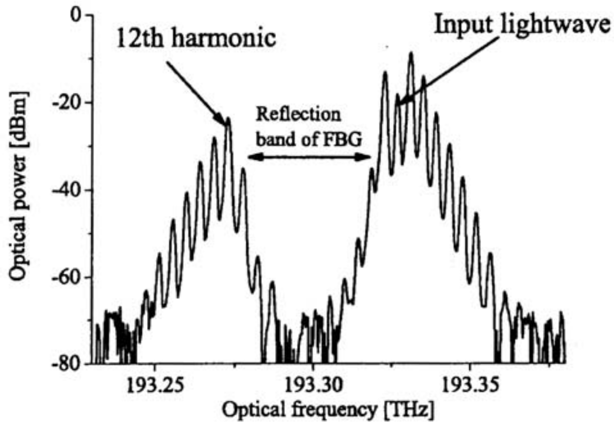

Fig. 4 Optical spectrum of output lightwave.

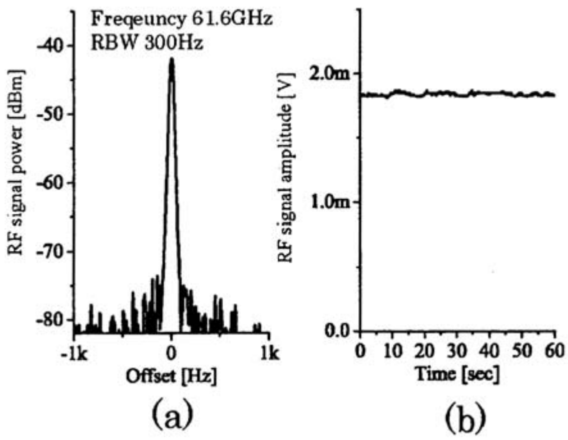

Fig. 5 Millimetre-wave (61.6 GHz) generated from rf-signal of 4.4 GHz, using the hybrid reciprocating optical modulator. (a) RF spectrum with the resolution bandwidth of 300 Hz. (b) Time domain profile.

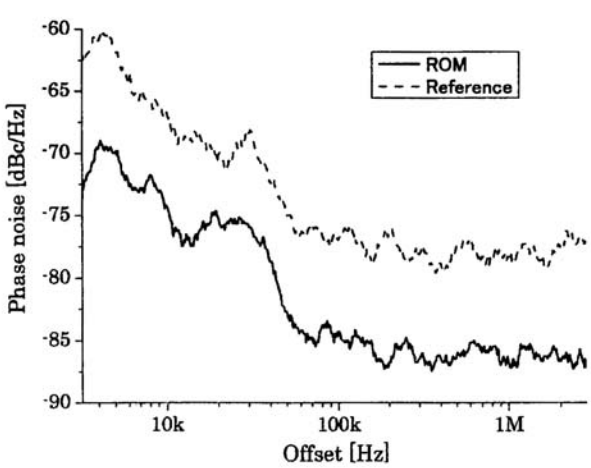

Fig. 6 Phase noise of millimetre-wave generated by ROM, and that of reference signal. The reference signal at 61.6 GHz (dashedline) was generated by using a signal generator (Agilent 83650B) and an up-converter (Agilent 83557A),

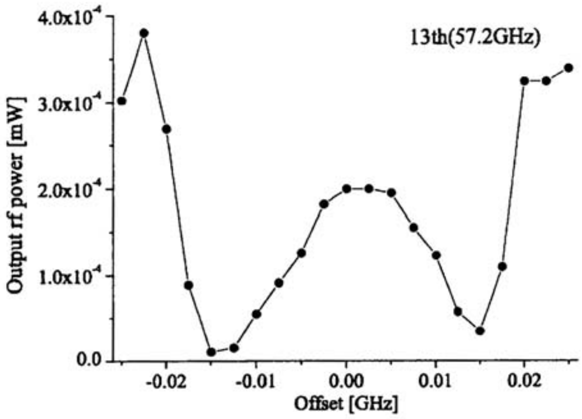

Fig. 7 Intensity of 13th order millimetre-wave, as a function of input rf frequency (detuning from 4.4 GHz).

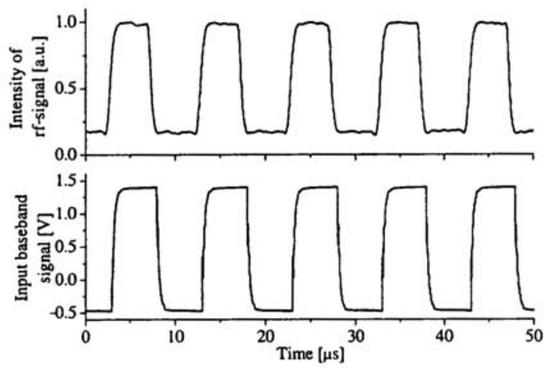

Fig. 8 Intensity modulation of 14th order millimetre-wave (61.4 GHz) by a baseband signal (100kHz rectangular pulse trains).

4. Conclusions

We demonstrated generation of optical harmonics and millimetre-waves, by using a hybrid reciprocating optical modulator consisting of a pair of FBGs and an optical phase modulator. 61.6 GHz millimetre-wave was obtained from 4.4 GHz signal. The phase noise of the millimetre-wave was -74.3 dBc/Hz at 10 kHz offset. The line width of the millimetre-wave was smaller than 300 Hz. The intensity was also stable, without using stabilization feedback control. We also demonstrated intensity modulation of the generated millimetre wave by applying a baseband signal to the modulator without using another electric or optical modulator. The intensity of the millimetre wave can be controlled by a signal whose amplitude is much smaller than the halfwave voltage of the modulator.

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