Reciprocating Optical Modulation for Harmonic Generation

Tetsuya Kawanishi, Masahide Sasaki, Shinichi Shimotsu, Satoshi Oikawa, and Masayuki Izutsu

***Abstract*—n this letter, the authors propose a novel optical modulation system for generating high-order harmonics, by using two filters placed at the optical input and output ports of an optical modulator. By reciprocating optical modulation at 30 GHz, the sixth-order harmonic, whose frequency is shifted by 180 GHz, is generated effectively.**

***Index Terms*—Harmonic generation, millimeter wave, optical filter, optical modulation.**

I. INTRODUCTION

OPTICAL modulators have important applications in optical and wireless telecommunication networks, Such as broad-band optical modulation up to 40 GHz [l]-[3] for trunk lines and narrow-band optical modulation for fiber-radio systems [4], [5]. They also can be used to construct a single-sideband modulator [6], [7], or a mode-locked laser system [8]. However, it is difficult to modulate lightwaves directly at a high frequency, such as a millimeter-band electric signal over 100 GHz, mainly due to the metallic loss at modulating electrodes. Concerning to obtain lightwave components modulated at a higher frequency, one may apply a high-power electric signal so that high-order harmonic components are generated due to nonlinearity of the modulator. Thus, we can obtain a modulated lightwave whose frequency is higher than that of the electric signal fed to the modulator. But, the effirciency of high-order harmonic generation is usually very small.

In this letter, we propose a simple optical modulation system that can generate high-order harmonics effectively, by using two filters placed at the optical input and output ports of an optical modulator. In this method, called reciprocating optical modulation, a part of sideband components is fed to the optical modulator again, to generate specific sideband components effectively. The desired sideband components are taken out from the modulator, without recycling for harmonic generation, whereas in mode-lock lasers and optical comb generators, all of the generated sideband components are recycled into the modulator regardless of the optical frequency [8], [9]. Thus, the desired sideband components are enhanced effectively, without spreading out the optical power over undesired sideband components.

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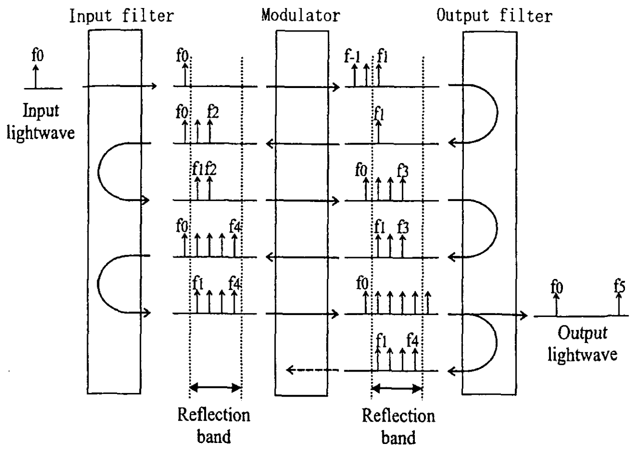

Fig l. Principle of harmonic generation

II. PRINCIPLES 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 (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 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's function of nth 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 confmed 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

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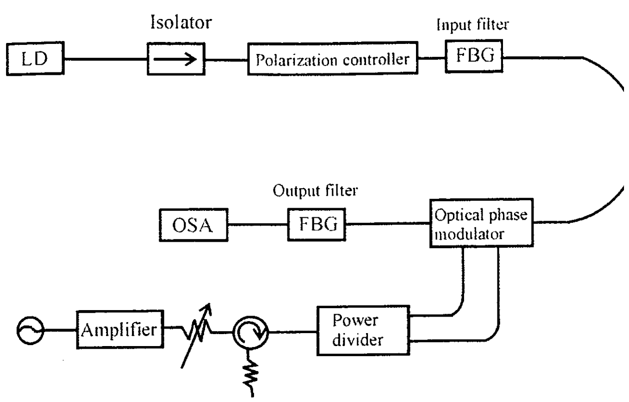

Fig. 2. Experimental set up

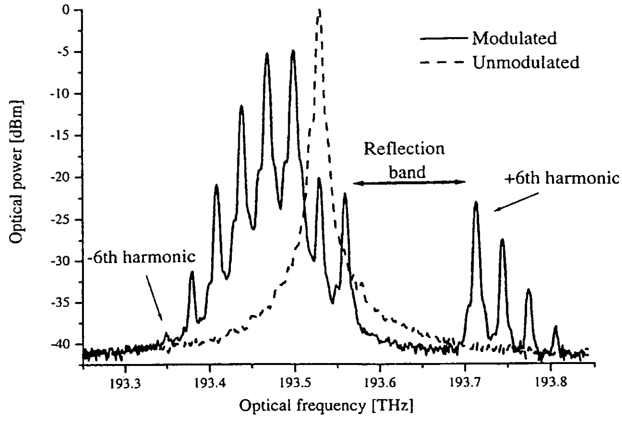

Fig.3 Spectrum of output lightwave for bidirectional feedlng.

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 the fifth-order harmonic generation is shown in Fig. 1. We suppose that the two filters reflect the spectrlun components f_{+1}, f_{+2}, f_{+3}, and f_{+4}. For simplicity, the amplitude of the electric signal is assumed to be so small that (1) can be approximated by $J_0(\Delta\phi)\ \exp[i2\pi f_0]$ + $J_1(\Delta\phi)\ \exp[i2\pi f_{+1}]$ + $J_{-1}\ (\Delta\phi)\ \exp[i2\pi f_{-1}]$. This system operates in the following steps (See Fig.1): l) the upper and lower sidebands whose frequencies are f_{+1} and f_{-1} , respectively, are produced by the modulator; 2) the upper sideband f_{+1} is reflected by the output fllter; 3) the reflected lightwave is modulated again by the modulator, and the spectrum components f_{+2} and fo are generated; 4) the input filter reflects component f_{+2}, so the modulator generates components f_{+3} and f_{+1} ; and 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}, . . . , f_{+n}, the component $f_{+(n+1)}$ can be generated through several iterations of the above steps.

III. Experiments and discussions

Fig. 2 shows the experimental setup of our system. A traveling-wave-type $LiNbO_3$ optical phase modulator, whose V_π (voltage required for π-phase shift) is 5.5 V at dc, is used to generate sidebands. A modulator of this type usually has an electric input port and an electric output port. In conventional traveling wave operation, an electric modulation signal is applied to the input port and the output port is terminated. In our setup, on the other hand, an electric sinusoidal RF signal is applied simultaneously to two electric ports of the modulator through a circulator and a power divider as shown in Fig. 2. Thus, the forward and backward lightwaves can be modulated by the forward and backward traveling waves excited on the electrode of the modulator. The electric signal from a signal generator is fed to the circulator through an amplifier and an attenuator. We call this feeding setup bidirectional feeding. Thus, the feeding setup in the conventional traveling-wave operation is called unidirectional feeding in this letter. Spectrum components, which contain the effect of the reciprocating modulation, are enhanced both in the unidirectional and the bidirectional feeding, but the enhancement in the unidirectional feeding is smaller than bidirectional. The frequency of the electric signal is about 30 GHz. The unmodulated lightwave from a laser diode (LD) is fed from the input filter through an optical isolator and a polarization controller. The optical frequency of the lightwave from the LD is 193.528 THz (1550.16 nm). Both the input and output filters are fiber Bragg gratings (FBGS), whose reflection band has a center optical frequency of 193.611 THz (1549.5 nm) and bandwidth of 162.3 GHz, so they reflect the spectrum components f_{+1} , f_{+2}, f_{+3}, f_{+4}, and f_{+5}. The optical path length from the filters to the modulator is 3.80 m (the physical path length is 2.53 m), so the delay time between two successive modulation steps is 25.3 ns.

The spectrum of the output lightwave from the port of the output filter is measured by an optical spectrum analyzer (OSA). It is shown in Fig. 3. The unmodulated optical power at OSA is adjusted to 0 dBm. The power and frequency of the electric signal fed to each port are 27.3 dBm and 30.002 GHz, respectively. The spectrum for unidirectional feeding is also shown in Fig. 4 for comparison. The spectrums from the output filter are steady without any stabilization. The output lightwave consists of both lower (f_{-1}, f_{-2}, . . .) and upper (f_{+6}, f_{+7}, . . .) sidebands, as shown in Figs. 3 and 4. High-order lower sidebands (f_3, .f_4, • • •), whose optical frequencies are smaller than 193.528 THz, are not in the reflection band of the filters. Thus, the dominant part of the lower sidebands are due to the nonlinearity of the modulator described by (1), and we may assume that the effect of the reciprocating modulation is small. Actually, the intensities of the first and second lower sidebands shown in Fig. 3 are nearly equal to those of the unidirectional feeding shown in Fig. 4. By applying (1) to the lower sideband intensities for unidirectional feeding. we estimated that $\Delta\phi$ is 2.23 rad, and that V_π at 30 GHz is 10.7 V. Upper sidebands below the sixth order are reflected by the filters, so the intensities of these components are small in the output lightwave.

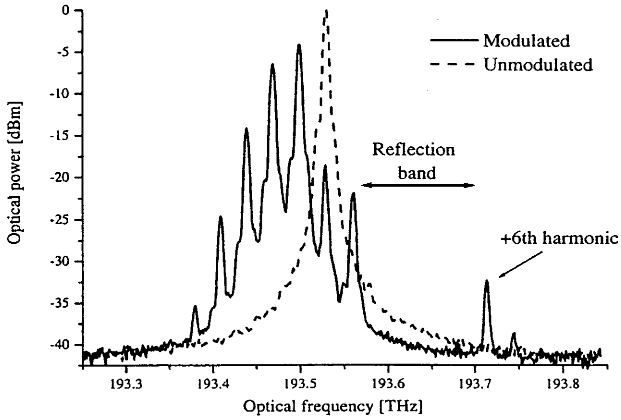

Fig. 4. Spectrum of output lightwave for unidirectional feedlng.

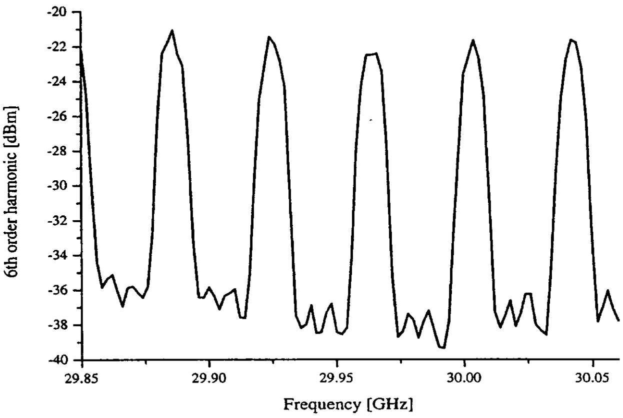

Fig. 5. Intensity of sixth harmonic generated by the reciprocating modulation.

On the other hand, the intensities of upper sidebands above the fifth order are larger than those of the lower sidebands. These components are enhanced by the reciprocating modulation. The effect in bidirectional feeding is much larger than in unidirectional feeding. For f_{+6}, the ratio between the bidirectional and the unidirectional operations is 4.8 dB. This is because the backward lightwave, as well as the forward lightwave, is modulated effectively in the bidirectional feeding. The f_{+6} intensity of bidirectional feeding is – 23.1 dBm. The f_{-6} intensity of unidirectional, is smaller than background noise level, but it can be estimated to be – 51.7dBm by using (1) and $\Delta\phi$. Thus, the enhancement factor f'or the sixth harmonic, which corresponds to the ratio of the bidirectional f_{+6} and unidirectional f_{-6}, is 28.6 dB.

When the delay time between two successive modulation steps is an integer multiple of $1/f_m$, the phase of the modulated signals is matched at each modulation step. Without matching the phase, the high-order harmonics cannot be generated effectively. Thus, the intensity of harmonics generated by the reciprocating optical modulation strongly depends on the frequency of the electric signal applied to the modulator. Fig. 5 shows the dependence of the sixth-order harmonic intensity on the electric signal frequency. The intervals between the peaks are 39.7 MHz, which corresponds to a period of 25.2 ns. This result is consistent with the delay time obtained from the optical path length.

IV. Conclusion

We have proposed a novel optical modulation system for generating high-order harmonic by using two filters put at optical input and output ports of an optical modulator. Generation of the sixth-order harmonic is enhanced in a factor of 28.6 dB by the reciprocating optical modulation.

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