

## Reciprocating optical modulator with resonant modulating electrode

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A reciprocating optical modulator consisting of two optical filters and an optical phase modulator that has a resonant electrode to enhance modulation efficiency at a particular frequency is proposed. Lightwave reciprocates in the modulator, where the optical phase modulator placed between the two optical filters acts both on forward and backward lightwaves.

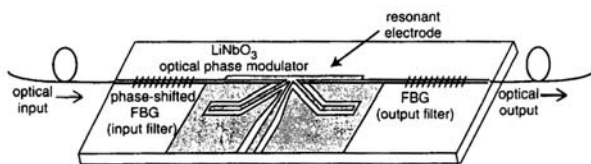
*Introduction:* High-order sideband generation using electro-optical modulation is a key technology for optical pulse sources and radio-on-fibre systems [1, 2]. A reciprocating optical modulator (ROM), consisting of a pair of optical filters and an optical phase modulator, can generate high-order sideband components effectively, where one of the optical filters is placed at the optical input port (input filter) and the other is at the output port (output filter). Thus, by using an ROM, we can obtain a lightwave modulated by an RF signal whose frequency is an integer multiple of an electric RF signal applied to the modulator. Recently, we demonstrated generation of a lightwave modulated by a millimetre-wave, by feeding a microwave signal to an ROM. In addition, the intensity of the high-order sideband components in the output can be controlled by an electric voltage applied on the phase modulation section in the ROM. Thus, a lightwave modulated by a millimetre-wave signal that is also modulated by a baseband signal, by means of an ROM [3]. This scheme is very useful for transmitters in radio-on-fibre systems.

In previous work [3], we used travelling-wave electrodes in the phase modulation sections, to obtain effective modulation in microwave or millimetre-wave bands. The velocity of the electric signal on the electrode is almost equal to that of the lightwave propagating in the waveguide under the electrode. The modulation process can be in-phase along a long electrode, so that we can obtain effective modulation even in millimetre-wave bands. In the travelling-wave electrode, the electric signal interacts effectively only with the lightwave propagating along the electric signal, while it does not with the counter-propagating lightwave. However, lightwaves reciprocate in ROMs, so that we have to feed both forward and backward electric signals to travelling-wave electrodes, in order to obtain effective reciprocating modulation processes. As a result, the feeding circuits were complicated in the previous work [3]. In this Letter, to overcome this difficulty, we used a resonant-type electrode in the phase modulator section, where the modulation efficiency can be enhanced at a designed resonance frequency. A double-stub structure, consisting of two modulating electrodes and two stubs, is a promising electrode arrangement [4], which gives bidirectional effective phase modulation by feeding a single RF signal. The length of the double-stub structure is much less than conventional travelling-wave electrodes, so that we can reduce the delay in the ROM modulation processes, which determines the response time to the baseband modulation of the high-order sideband components.

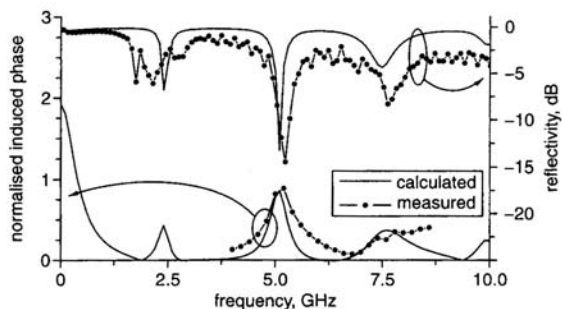
In addition, we employed a phase-shifted fibre Bragg grating (FBG) as an input filter, to obtain high-order sideband components both in upper sideband (USB) and lower sideband (LSB) (high-order double sideband components, henceforth). A phase-shifted FBG has a very narrow passband in its reflection band. The output filter was a conventional FBG whose centre wavelength was equal to that of the input filter. When the input wavelength was in the passband of the input filter, both USB and LSB reciprocate between the input and output filters, so that high-order double sideband components can be generated effectively. The output lightwave has optical beat components whose frequencies are higher than  $2Nf_m$ , where  $f_m$  is the frequency of the RF signal fed to the modulator.  $N$  is the number of the reciprocation. This is in contrast to an ROM consisting of a pair of conventional FBGs having the same

reflection band. Lightwave in the reflection band reciprocates several times between the filters, when the input lightwave is out of the band and very close to the edge of the band. However, only one of the sideband components would be in the reciprocating modulation process. The other component does not reciprocate in the modulator, because it is out of the reflection band. Thus, the frequency of the beat components are around  $Nf_m$ .

**Device structure:** Fig. 1 shows the fabricated integrated reciprocating optical modulator, where the FBGs were fixed in V-grooves on SiO<sub>2</sub> substrates and directly attached to a LiNbO<sub>3</sub> modulator chip. The phase-shifted FBG has a narrow passband in the reflection band. The bandwidth of the passband was less than 2 GHz. The output filter was a conventional FBG with a heater to let the centre wavelength equal that of the input filter. The input lightwave should be in the passband of the input filter. A double-stub structure, having a pair of stubs and modulating electrodes, was used as a resonant electrode, where the electrodes and stubs were open-ended to let DC bias voltage be applied on the waveguide of the modulator [4]. The resonant frequency of the electrode was designed to be equal to the inverse of delay in a reciprocation process, to let the successive modulation process be in-phase.



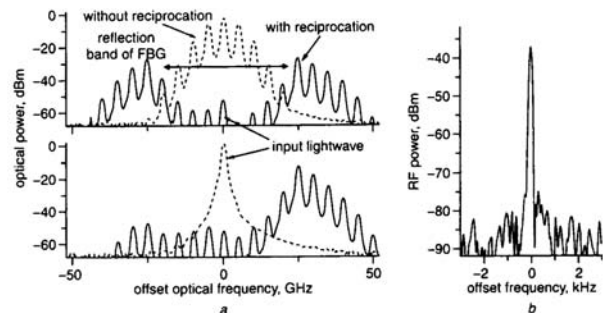
**Fig. 1** Reciprocating optical modulator with resonant electrode



**Fig. 2** Frequency responses of double-stub structure: electric reflectivity ( $S_{11}$ ) and optical response (normalised induced phase)

**Experiments:** Fig. 2 shows frequency responses (normalised induced phase and electric reflectivity) of the double-stub structure, whose designed resonant frequency was 5 GHz. The normalised induced phase is an index showing modulation efficiency normalised by the length of the modulating electrode. The electric reflectivity of the double-stub structure would have a dip at the resonant frequency. The lengths of each electrode and stub were 13.82 and 7.98 mm, respectively. The chip length of the LiNbO<sub>3</sub> modulator chip was 48.75 mm. The calculated electric responses were obtained by an equivalent circuit model [4]. The normalised induced phase was measured by using our proposed method where the half-wave voltage and chirp parameter can be obtained from output optical spectra [5]. The measured half-wave voltage at 5.0 GHz was 6.2 V. The experimental results agree well with the calculated or designed responses. The upper plots in Fig. 3a show the output spectrum of the fabricated ROM and that of the conventional optical phase modulation, where the input RF power and frequency were, respectively, 19.8 dBm and 5 GHz. Optical power and frequency of the input lightwave were, respectively, 4.2 dBm and 192.956 THz. Sideband components lower than fifth order were in the reflection band, so that fifth or sixth order harmonic components were generated effectively. The output spectrum can be controlled by changing the input optical frequency, DC bias voltage applied to the electrode, or the temperature of the modulator. The lower plots in Fig. 3a show the output spectrum of the optimised condition for high-order USB generation. The conversion efficiency of the fifth order harmonic was -13.3 dB, while that of the conventional phase modulation was -67.3dB. The spectrum of

millimetre-wave which was generated by feeding the ROM modulated lightwave to a high-speed photodetector is shown in Fig. 3b. The linewidth was narrower than 100 Hz.



**Fig. 3** Output spectra

a Optical spectra: lightwaves modulated by ROM and by conventional phase modulation (upper), optimised for high-order USB generation (lower)  
b Electric spectra: millimetre-wave (50 GHz) generated from the ROM output. The resolution bandwidth was 100 Hz

**Conclusion:** We have proposed a reciprocating optical modulator with a resonant modulating electrode, for generation of high-order sideband components, where the modulation section can act both on forward and backward lightwaves simultaneously. A lightwave signal having a 50 GHz beat component was generated effectively from a 5 GHz signal.

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