

Optical modulation with a single sideband and carrier suppressed

S. Granieri¹ and A. Siahmakoun
Department of Physics and Applied Optics
Rose Hulman Institute of Technology
Terre Haute, Indiana 47803.

D. Thelen
Technology Service Corporation,
Bloomington, Indiana 47404.

ABSTRACT

A single sideband suppressed-carrier (SSB-SC) optical modulator is demonstrated. The sideband is suppressed by means of a fiber Mach-Zehnder interferometer with amplitude electro-optical modulators in each branch. The attenuation of the carrier is achieved by proper biasing of the integrated modulators. The proposal was demonstrated by modulating at 285 MHz. Suppression of 30.8 dB in the carrier and 26.3 dB in the sideband were obtained.

Keywords: Optical modulation, Single sideband suppressed carrier modulation, Fiber interferometer, RF signal processing

1. INTRODUCTION

The advantages of suppressing the carrier component in the modulation stage are well known from the signal processing aspect in communication systems. It is also well known that transmission of the carrier is a waste of power since the information is carried by the sidebands. Furthermore, the suppression of the carrier leads to improve important characteristics of the fiber optic link such as dynamic range and noise figure. A direct way to increase dynamic range in fiber optic links is to increase the optical power at the detection stage. However, once the saturation level in the detector is reached, increasing the optical power is no longer an effective solution. Typical application of electro-optic modulators requires linear modulation at the half-intensity transmission bias point. Although it eliminates even-order distortion terms but a large carrier component is generated as well. Particularly, in optical transmission of analog data in the C/L band the carrier suppression allows the use of erbium-doped optical amplifiers after the modulation stage. On the other hand conventional double sideband modulation with direct detection is hindered by chromatic dispersion. This effect causes the transmission of millimeter-waves over standard optical fiber is limited to a few kilometers. Transmitting the signal in a single sideband format helps to diminish the optical dispersion penalties.

The optical analog to the single sideband suppressed-carrier (SSB-SC) modulator has been implemented using a fiber Sagnac interferometer [1,2]. Single sideband modulator with carrier has been proposed and demonstrated using a Mach-Zehnder interferometer [3,4]. In Ref. [5] the sideband suppression is also achieved using an amplitude modulator in tandem with a phase modulator.

In this paper we propose and experimentally demonstrate a direct implementation of a SSB-SC optical modulator using two commercial Mach-Zehnder optical modulators (MZM) inside of a fiber-optic Mach-Zehnder interferometer. The suppression of the carrier is obtained by setting the bias voltage of both MZM in the lowest intensity transmission point, while a simple the adjustment of the phase shift in a fiber interferometer attenuates one of the sidebands. Section 2 describes the modulator design and some theoretical results are developed. In section 3 we present the experimental results, discuss some conclusions, and possible improvements.

¹ Postal Address: 5500 Wabash Ave., Terre Haute, IN 47803. Phone: 812-877-8080, Fax: 812-877-8023, E-mail: granieri@rose-hulman.edu.

2. THEORY

The experimental scheme of our SSB-SC optical modulator is shown in Fig. 1. This architecture is similar to the Hartley microwave SSB generator used in electrical modulation. The optical field at the input is split into the two arms of a fiber-optic Mach-Zehnder interferometer by means of a fiber coupler. The field at each branch may be expressed by

$$E_{01}(t) = E_0 / \sqrt{2} \cos(\omega_c t), \quad (1a)$$

$$E_{02}(t) = E_0 / \sqrt{2} \cos(\omega_c t + \Delta\phi), \quad (1b)$$

where E_0 and ω_c are the field amplitude and the optical carrier frequency respectively, and $\Delta\phi$ is the relative phase shift. Two integrated electro-optical Mach-Zehnder modulators (MZM) produce the amplitude modulation of the optical carrier. These modulators are driven with the same RF signal with a phase difference. In order to simplify the

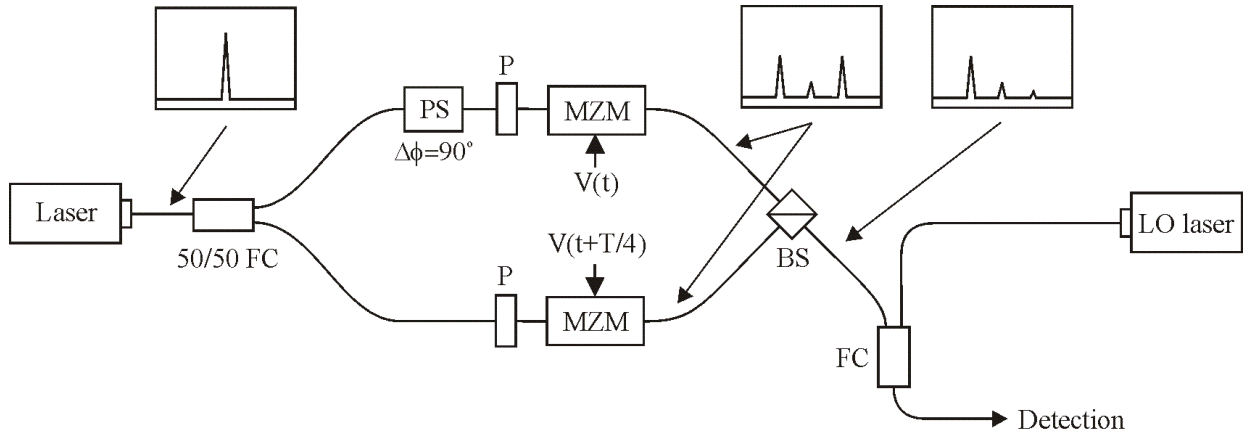


Fig. 1: Experimental setup showing the single side-band suppressed carrier optical modulator and the heterodyne detection configuration. The schematic shows the spectral components of a single-tone modulation along the system.

analysis the MZMs are considered identical, however, the effect of differences in their characteristic parameters over the performance of the proposed modulator is mentioned in the next section. If the MZM are driven by a single-tone RF signal, the optical output can be written as

$$E_1(t) = E_{01}(t) \cos\left(\frac{\pi V_{DC}}{2 V_\pi} + \frac{\pi V_m}{2 V_\pi} \cos(\omega_m t)\right), \quad (2)$$

assuming a lossless device and V_{DC} being a dc-bias term, V_m and ω_m the amplitude and angular frequency of the electrical signal respectively, and V_π the half-wave voltage [7]. In order to find the condition to suppress the carrier component we expand Eq. (2) in terms of Bessel function as

$$E_1(t) = E_0 / \sqrt{2} \cos(\omega_c t) \left\{ \cos\left(\frac{\pi V_{DC}}{2 V_\pi}\right) J_0\left(\frac{\pi V_m}{2 V_\pi}\right) + 2 \cos\left(\frac{\pi V_{DC}}{2 V_\pi}\right) \sum_{n=1}^{\infty} (-1)^n J_{2n}\left(\frac{\pi V_m}{2 V_\pi}\right) \cos[2n\omega_m t] - \right. \\ \left. - 2 \sin\left(\frac{\pi V_{DC}}{2 V_\pi}\right) \sum_{n=0}^{\infty} (-1)^n J_{2n+1}\left(\frac{\pi V_m}{2 V_\pi}\right) \cos[(2n+1)\omega_m t] \right\}, \quad (3)$$

where $J_n()$ is the n-order Bessel function. The first term in this equation is the carrier component, and the second and third terms are the odd and even-order sidebands respectively. As can be seen from Eq. (3), if the dc bias term is

set as $V_{DC} = V_{\pi}$, the carrier and the even-order side-bands are suppressed. This condition corresponds to the lowest intensity transmission point in the MZM transfer function.

The output signal of both MZMs is recombined by means of a beam splitter pigtailed with polarization maintaining fiber. Using Eq. (3), the output field can be written as

$$E(t) = E_0 / \sqrt{2} \left[\sin\left(\frac{\pi}{2} \frac{V_m}{V_{\pi}} \cos(\omega_m t)\right) \cos(\omega_c t) + \sin\left(\frac{\pi}{2} \frac{V_m}{V_{\pi}} \cos(\omega_m t + \Delta\Phi)\right) \cos(\omega_c t + \Delta\phi) \right], \quad (4)$$

where the dc bias was chosen in order that the condition for carrier suppression is fulfilled, and $\Delta\Phi$ is the phase shift between the electrical signals applied to both MZMs. The output field of Eq. (4) can be written in terms of Bessel functions using Eq. (3) as

$$E(t) = E_0 / \sqrt{2} J_1\left(\frac{\pi}{2} \frac{V_m}{V_{\pi}}\right) \left\{ \cos[(\omega_c + \omega_m)t] + \cos[(\omega_c + \omega_m)t + \Delta\phi + \Delta\Phi] + \right. \\ \left. + \cos[(\omega_c - \omega_m)t] + \cos[(\omega_c - \omega_m)t + \Delta\phi - \Delta\Phi] \right\} + \text{high order terms}. \quad (5)$$

As can be noted from Eq. (5), by setting the phase difference between carriers, $\Delta\phi$, and between the electrical signals, $\Delta\Phi$, as $\pm 90^\circ$, one of the sidebands is eliminated. The 90° phase shift in the electrical signals can be obtained driven one MZM with the signal and another with its Hilbert transform or, in narrow-band applications, placing the MZM in an asymmetric way with respect to the beam splitter. In the narrow-band case the time delay in the optical path provides the desired phase difference.

3. EXPERIMENT AND CONCLUSIONS

A semiconductor laser provides 18.2 dBm of optical power for the input carrier at 1552 nm wavelength. A pigtailed polarizer (P) placed before each MZM grants the linear polarized state at the input port in each branch of the fiber interferometer. The modulators are a broadband SDL integrated electro-optic Mach-Zehnder on LiNbO_3 ,

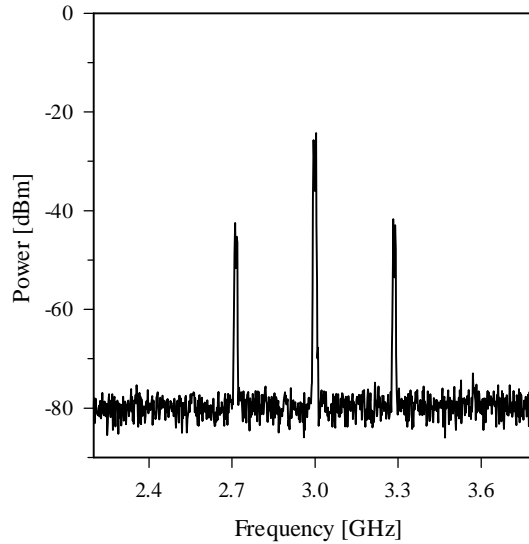


Fig. 2: Heterodyned optical spectrum for $\Delta\phi=0$, and the electro-optical modulators biased at the half-intensity transmission point (linear response zone).

with half-wave voltages of 5.1 V and 4.8 V, insertion losses of 4.1 dB and 4.2 dB at 1550 nm, and 10 GHz bandwidth. The 50/50 beam splitter (BS) is pigtailed with polarization maintaining fiber in order to achieve stable polarization of the light in the interferometer. We choose the heterodyne detection method to shift the optical

spectrum towards the electrical-frequency domain. The band of interest is selected by mixing the optical output of the fiber interferometer with a local oscillator via a second fused-fiber coupler. A Santec single mode semiconductor laser tunable between 1480-1600 nm with 9 dBm optical power is used as local oscillator. Using this configuration, the coupler output is detected with a 30 GHz Discovery Semiconductors photodetector. The output spectral components are visualized with a TEK4202 RF spectrum analyzer.

In order to demonstrate the feasibility of the proposal, we perform the suppression of the sideband and carrier by modulating the optical carrier with a sine wave at a frequency of 285 MHz and power level of 5 dBm. The 90° phase shift in the electrical signals is obtained with one of the MZMs delayed by $T/4$ being T the period of the sinusoidal wave. The phase difference between carriers is produced locating a sensible fiber stretcher in one branch

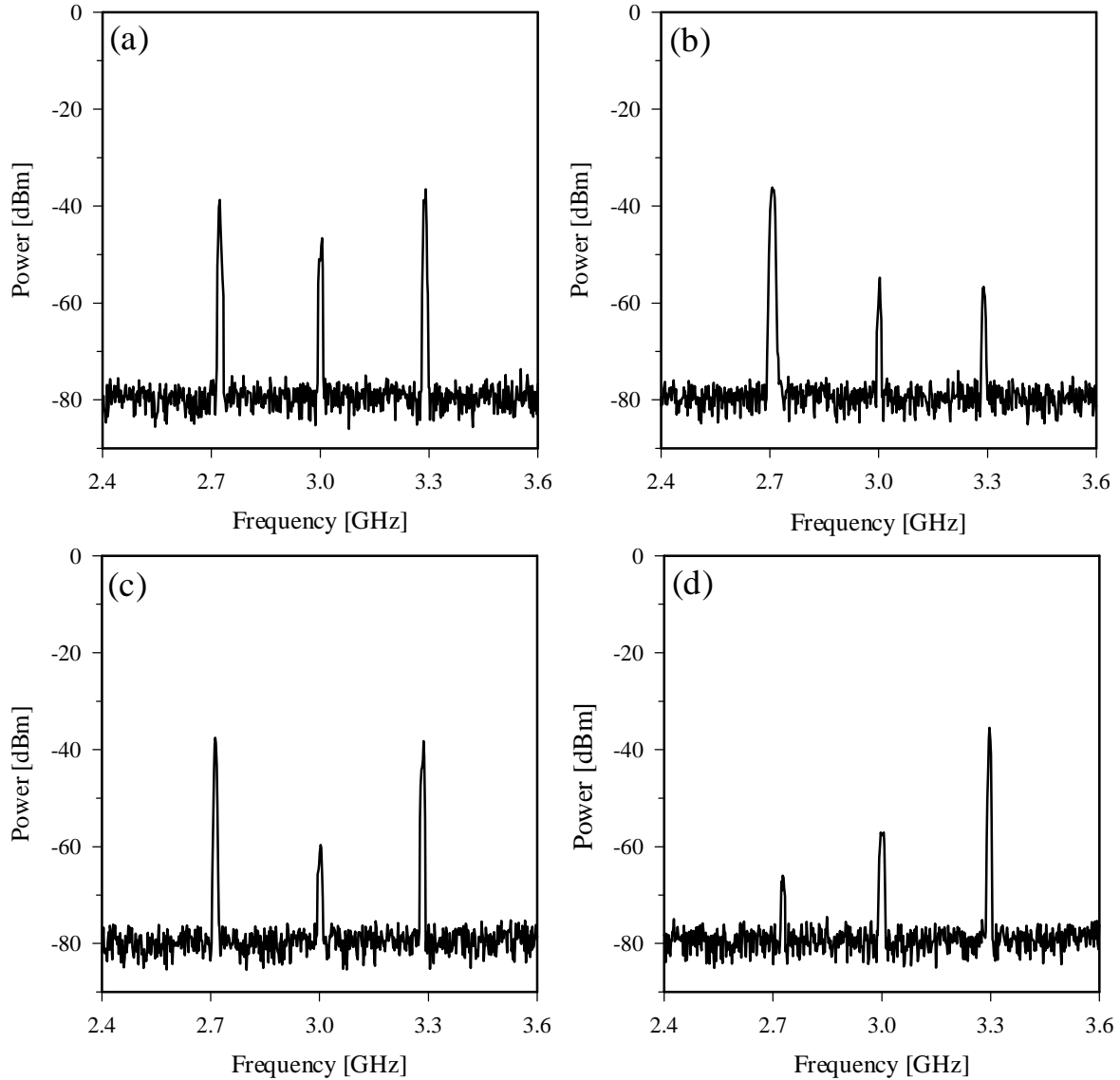


Fig. 3: Heterodyned optical spectrum for a single tone modulation with the electro-optical modulators biased at the minimum intensity transmission point (carrier suppressed) for: (a) $\Delta\phi=0$; (b) $\Delta\phi=\pi/2$; (c) $\Delta\phi=\pi$; and (d) $\Delta\phi=3\pi/2$.

of the fiber interferometer. The fiber stretcher is driven by a piezo-electric transducer to get complete 360° phase shift in cycles of 70 V. Fig. 2 shows the heterodyned optical spectrum centered at 3 GHz when both MZMs are biased for linear intensity operation and the phase shift between optical carriers is set to $\Delta\phi=0^\circ$. The measured

power values for the carrier and first sideband components are -24.2 dBm and -41.7 dBm respectively. In Fig. 3 the optical spectrums are shown for the case when the carrier suppression condition is fulfilled. In this case, the modulators are biased for working at the minimum transmission point. In Fig 3a through 3d the phase difference between optical carriers is $\Delta\phi = 0^\circ, 90^\circ, 180^\circ$ and -90° respectively. It can be seen when $\Delta\phi$ is set to $\pm 90^\circ$, the right and left sidebands are attenuated alternately. The measured suppression of the sideband in Fig. 3b and 3d is 26.3 dB and 30.4 dB respectively. Carrier suppression of 32.8 dB is estimated by comparison between the optical spectrum shown in Fig 2 and ones shown in Fig. 3d and 3d. Suppression of the sideband is limited by the differences in the half-wave voltage of the MZMs and by the unbalanced optical power in the fiber interferometer.

In summary, we have presented a straightforward optical implementation for obtaining SSB-SC modulation of optical signals with commercially available modulators. Although the feasibility of this technique has been experimentally demonstrated at 285 MHz, the operation at higher RF frequencies will be mainly limited by the MZM bandwidth.

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