Photonic Mixers and Image–Rejection Mixers for Optical SCM Systems

Lu Chao, Chen Wenyue, and Jeffrey Fu Shiang

***Abstract*—Performances of subcarrier multiplexing (SCM) systems using Mach–Zehnder optical modulators for signal down conversion are studied in this paper. A photonic-image–rejection mixer is proposed to solve the image–frequency problem. The performance of the image–rejection mixer using nonideal system components is evaluated.**

***Index Terms*— Subcarrier multiplexing.**

I. INTRODUCTION

ANALOG optical-fiber links have attracted much attention in recent years. They have found applications in fiber-fed microwave cellular networks [1], multichannel cable television systems, and phase-array antenna networks. One such system is the microwave subcarrier multiplexing (SCM) system which has been widely used [2]. In a conventional SCM system, the optical receiver has to be able to receive all the subcarrier channels before detection and demodulation of each individual channel can be carried out. Because of the wide-band nature of the SCM signals, receiver design can be difficult. In addition, the system is not flexible because when the system capacity has to be upgraded (i.e., adding more channels) the optical receiver must be replaced. To solve these problems, several schemes have been proposed. These include coherent SCM systems [2], optical prefiltering SCM systems [3], and optical SCM systems using microwave–optical mixing [4]. The first system requires a complicated control scheme to offset-lock two optical carriers, while in the second scheme the passband of a extremely narrow-band optical filter has to be locked to the selected optical microwave frequency. The SCM systems using an optical microwave mixer offers a more flexible alternative to the first two choices.

This paper is organized as follows. In Section II, the performance of SCM systems using Mach–Zehnder electro-optical modulators as microwave–optical mixers are studied. It is shown that image frequency can be a problem in such systems. In Section III, we propose a novel microwave–optical image–rejection mixer to solve the image–frequency problem. Performance limitations of the mixer due to nonideal system components are discussed. Finally, discussions and conclusions are presented in Section IV.

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II. SYSTEM DESCRIPTION

In a typical SCM system using microwave–optical mixing for signal down conversion [4], subcarrier multiplexed multichannel signals are either used to directly modulate the injecting current of a laser diode or to drive a Mach–Zehnder external modulator to modulate the output power from a laser diode. For a direct modulated system, the output optical power at the transmitter is given by

$$P_o = P_l\left(1 + \sum_{i=1}^{N} m_i \sin(2\pi f_i t + \alpha_i(t))\right). \tag{1}$$

While for a laser diode modulated using an external modulator we have

$$P_o = \frac{P_l T_D}{2}\left(1 - \sin\left(\frac{\pi V}{V_\pi}\sum_{i=1}^{N}\cos(2\pi f_i t + \alpha_i(t))\right)\right). \tag{2}$$

Where P_l is the laser-diode output power and other parameters follow the same notations as [4]. After the signal is transmitted through a certain length of fiber, a microwave–optical mixer using a Mach–Zehnder optical modulator is used to mix the incoming signal with a microwave tunable local oscillator (LO). This will convert the required channel frequency to a predetermined intermediate frequency (IF). This can be followed by an optional fiber amplifier to boost the received signal further before an optical receiver is used to convert the optical signal to an electrical signal. An electrical bandpass filter can then be used to reject unwanted signals followed by a demodulator to recover the original transmitted signal.

Taking into consideration the excess loss L_e caused by the optical fiber and connectors, ignoring dc, LO carrier frequency, and harmonic terms, we can expand (1) and (2) in a series of Bessel functions [5]. The carrier-to-noise ratio at the output of the bandpass filter is given as a result of the direct modulation system, shown in (3) at the bottom of the following page, and for the external modulated system, shown in (4) at the bottom of the following page, where σ_{id}^2 is the mixing-product term between f_{LO} and the intermodulation-product terms of subcarrier channels generated by the laser diode or the first external modulator, σ_{xd}^2 is the mixing-product term generated by the harmonics of f_{LO} and intermodulation-product terms of either the laser diode or the first external modulator. Other notations follow [4].

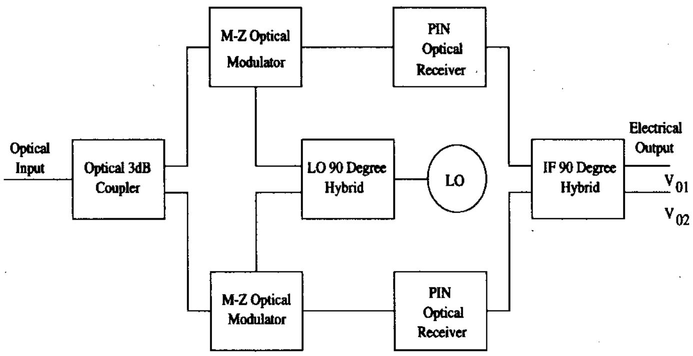

Fig. 1. Optical microwave–image–rejection mixer using Mach–Zehnder modulators.

In general, an image–frequency problem will exist (i.e., when two SCM channels are symmetrical to the LO frequency they will be converted to the same IF frequency, thus causing interference to each other). To avoid this problem, we should have

$$2f_{\mathrm{IF}} \geq f_{\max} - f_{\min} \tag{5}$$

where $f_{\max}$ and $f_{\min}$ are maximum and minimum frequencies of the subcarrier channels and $f_{\mathrm{IF}} = f_i - f_{\mathrm{LO}}$. The requirement given in (5) is necessary in order to avoid the image–frequency problem.

III. Optical Microwave-Image-Rejection Mixer

Equation (5) has set a lower boundary for IF frequency if image–frequency problems are to be avoided. This greatly limits one of the advantages of using photonic mixers for SCM-signal down conversion prior to signal detection (i.e., an optical receiver with a bandwidth much lower than the total SCM signal bandwidth can be used). Since the bandwidth of each individual SCM channel is usually much narrower than the overall SCM signal bandwidth, it is beneficial to find a way to reject the image frequency so that a lower IF frequency can be used. An image–rejection mixer based on two optical modulators is proposed here and illustrated in Fig. 1. An optical signal at the receiving end is split into two paths by a 3-dB optical coupler. Each path is fed to the input of one of the two identical optical modulators. The two modulators are biased at quadrature and driven by LO's with 90° phase differences. Optical outputs of the two modulators are detected by two low bandwidth optical receivers before the detected signals are used as inputs to a 90° hybrid. The final output is taken from one of the output ports of the hybrid.

The general input signal to the image–rejection mixer at the receiver is

$$P_{\mathrm{in}} = A\cos\omega_s t + B\sin\omega_m t \tag{6}$$

where $\omega_s = \omega_0 + \omega_{\mathrm{IF}}$ is the signal frequency and $\omega_m = \omega_0 - \omega_{\mathrm{IF}}$ is the image frequency of the signal. ω_0 and ω_{IF} are the LO and IF frequencies, respectively. If the two paths are balanced and the 90° hybrids are ideal, the two outputs of the image–rejection mixer are

$$V_{o1} = \frac{A}{4}\rho R J_1(m)\cos\omega_{\mathrm{IF}} t \tag{7}$$

$$V_{o2} = \frac{B}{4}\rho R J_1(m)\sin\omega_{\mathrm{IF}} t \tag{8}$$

where $m = \frac{\pi V_{\mathrm{LO}}}{2V_\pi}$ and ρ is the transimpedance of the optical receivers. The output V_{o1} has contribution only from signal channel A, while image signal B is completely absent. This indicates a complete rejection of the image frequency at one of the output ports.

However, in practical systems the two optical paths are usually not balanced. Several factors contribute to this: the two unbalanced outputs of the optical 3-dB coupler, differences in V_π, insertion loss and driving voltage of the two optical modulators, phase error of the 90° hybrids, polarization imbalance, and differences in the responses of the two optical receivers. When all these factors are taken into consideration, the output of the image–rejection mixer is given by

$$\begin{aligned} V_{o1} = \frac{A}{4}&((R_1\rho_1 T_D \alpha J_1(m_1)\cos\Delta\phi_1 \\ &+ R_2\rho_2 T_D(1-\alpha)X\cos\Delta\phi_2)\cos\omega_{\mathrm{IF}} t \\ &- R_2\rho_2 T_D(1-\alpha)Y\cos\Delta\phi_2)\sin\omega_{\mathrm{IF}} t) \\ &+ \frac{B}{4}((R_1\rho_1 T_D\alpha J_1(m_1)\cos\Delta\phi_1 \\ &- R_2\rho_2 T_D(1-\alpha)X\cos\Delta\phi_2)\cos\omega_{\mathrm{IF}} t \\ &- R_2\rho_2 T_D(1-\alpha)Y\cos\Delta\phi_2)\sin\omega_{\mathrm{IF}} t) \end{aligned} \tag{9}$$

where α is the percentage output from the output port of the 3-dB coupler. R_1, ρ_1, R_2, ρ_2 are responsivities and transimpedances of p-i-n diodes and optical receivers of the two optical paths, respectively. δ is the phase deviation from the quadrature of the LO hybrid and $\Delta\phi_1$, $\Delta\phi_2$ are the phase angle errors due to the intrinsic phase mismatch between the two arms of the modulators. m_1, m_2, m_{2a}, m_{2b}, X, and Y

$$\frac{C}{R} = \frac{\left(\frac{1}{2}RP_lT_DL_em_iJ_1\left(\frac{\pi V_{\mathrm{lo}}}{V_{\pi\mathrm{lo}}}\right)\right)^2}{\left(2e\left(\frac{1}{2}RP_lT_DL_e\right)+\langle i_{eq}\rangle^2+\left(\frac{1}{2}RP_lT_DL_e\right)^2\mathrm{RIN}\right)\mathrm{B_{BP}}+\sigma_{\mathrm{id}}^2+\sigma_{\mathrm{xd}}^2} \tag{3}$$

$$\frac{C}{R} = \frac{\left(\frac{1}{4}RP_lT_D^2L_eJ_1\left(\frac{\pi V_{\mathrm{lo}}}{V_{\pi\mathrm{lo}}}\right)J_1\left(\frac{\pi V}{V_\pi}\right)J_0^{N-1}\left(\frac{\pi V}{V_\pi}\right)\right)^2}{\left(2e\left(\frac{1}{4}RP_lT_DL_e\right)+\langle i_{eq}\rangle^2+\left(\frac{1}{4}RP_lT_DL_e\right)^2\mathrm{RIN}\right)\mathrm{B_{BP}}+\sigma_{\mathrm{id}}^2+\sigma_{\mathrm{xd}}^2} \tag{4}$$

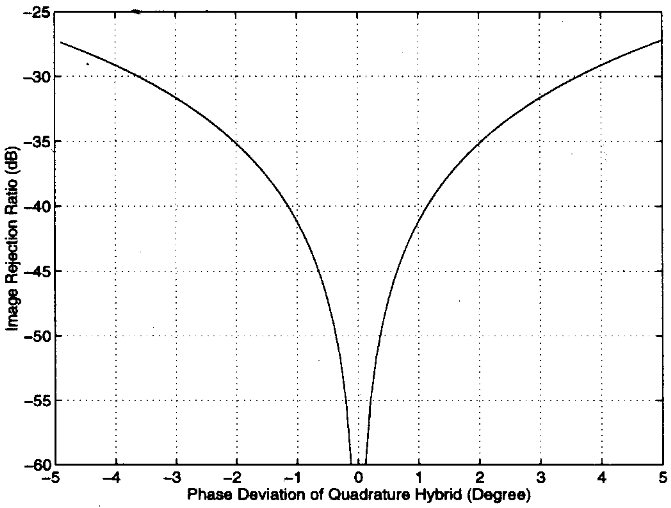

Fig. 2. Image–rejection ratio versus phase deviation of the 90° hybrid.

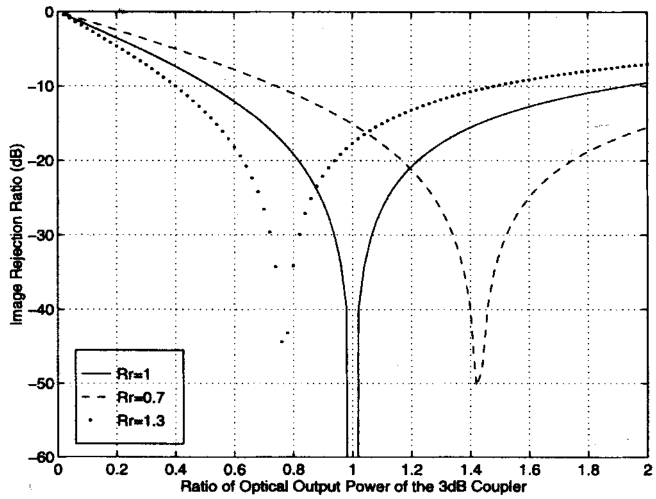

Fig. 3. Image–rejection ratio versus the ratio of the modulation indexes of the two optical modulators.

are defined as follows:

$$m_1 = \frac{\pi V_{\rm LO}}{V_{\pi 1}} T_D \alpha$$
$$m_2 = \frac{\pi V_{\rm LO}}{V_{\pi 2}} T_D (1-\alpha)$$
$$m_{2a} = m_2 \cos\delta$$
$$m_{2b} = m_2 \sin\delta$$
$$X = J_1(m_{2a})J_0(m_{2b}) + J_1(m_{2a})J_2(m_{2b})$$
$$Y = J_0(m_{2a})J_1(m_{2b}) + J_2(m_{2a})J_1(m_{2b}).$$

To evaluate the performance of the proposed mixer using nonideal components, we define an image–rejection ratio R_i as

$$R_i = 10 \log_{10} \frac{P_i}{P_s} \qquad (10)$$

where P_s and P_i are the power of the IF signal and image–frequency signal, respectively. The effect of phase deviation of the 90° IF hybrid on R_i is given in Fig. 2. The result shows that for a commercial 90° hybrid with deviation from quadrature within 3°, an image–rejection ratio of better than 30 dB can be achieved. To consider the effect of the imbalanced drive voltage and V_π for the two optical modulators, the ratio of the modulation indexes of the two modulators versus R_i is plotted in Fig. 3. The result indicates that if the difference of the modulation indexes is less than 0.8 dB, an R_i of better than 20 dB can be obtained. If we define the ratio of the transimpedance of the two optical receivers as $R_r = \frac{\rho_2}{\rho_1}$, the ratio of the modulation indexes of the two modulators versus R_i for different values of R_r have been plotted on the same diagram. The result shows that if $R_r = 0.7$ the image–rejection ratio will be reduced to −11 to −21 dB and for $R_r = 1.3$ the image–rejection ratio will be in the range of −13 to −30 dB.

IV. Discussions and Conclusions

When an image–rejection mixer is used in SCM systems with a photonic mixer, a much lower IF frequency can be used. However, a fixed 3-dB penalty will always be introduced due to the splitting of optical signals into two paths. In addition, the residual image frequencies due to nonideal components of the image–rejection mixer will restrict the maximum available carrier-to-noise ratio. Careful frequency planning, together with the use of the image–rejection mixer, will keep the image frequency to a minimum.

In this paper, we studied the performance of optical SCM systems using optical modulators for signal down conversion. It was shown that good system performance can be obtained. However, IF frequency is limited by the image frequency. To solve this problem. an image–rejection mixer using optical modulators was proposed. Studies of the mixer performance under nonideal system components were carried out. The results indicate satisfactory performance can be obtained if the optical powers for the two optical paths are carefully balanced. This requirement can be alleviated by specially designed system components such as dual modulators with matched parameters. Together with careful frequency planning, the image frequency can be kept to a minimum.

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Lu Chao, photograph and biography not available at the time of publication.

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