Fiber Optic Microwave Links Using Balanced Laser Harmonic Generation, and Balanced/Image Cancellation Laser Mixing

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Abstract—**This paper proposes three fiber optic link configurations for use in microwave transmission. Two laser diodes are used to generate balanced harmonics and the optical power from each diode is combined and detected by photodiodes. The fundamental and odd harmonics are suppressed and even harmonics added. The balanced and image cancellation laser mixing which utilizes a combination of microwave components and optical devices can suppress the local and image frequencies, respectively. These configurations are experimentally investigated at microwave frequencies and frequency suppression is successfully demonstrated.**

Introduction

A NUMBER of fiber optic links have been investigated for microwave and millimeter-wave signal transmissions [1]–[7]. The performance of optical devices is being improved and the maximum operating bandwidth has exceeded the *Ka*-band [8]–[10]. Another technique which can extend the bandwidth of fiber optic links is the utilization of the inherent nonlinearities of the optical devices, i.e., laser diodes [11], [12] and photodiodes [13]. A laser diode modulated by a high RF signal power near the relaxation oscillation frequency generates harmonics [11]. The generated harmonics can then be used as the carrier reference signal [5]. A photodiode nonlinearity can also produce harmonics and these can be used to convert the detected modulation signal frequency [13], [14]. Harmonics not only extend the fiber optic link bandwidth, but often generate undesired spurious signals. To suppress undesired spurious signals, microwave filters must be used.

In this paper, three fiber optic link configurations are proposed, that utilize the combination of microwave functional components (e.g., in-/out-of-phase combiners/dividers) and optical devices (e.g., laser diodes and photodiodes).These links can suppress undesired spurious frequencies generated by the laser diode nonlinearity. The phase of the RF signals supplied to the laser diode is determined by the microwave circuits. In addition to the fundamental laser diode RF frequency, harmonics or converted frequencies are received in the photodiodes. The RF signals detected by the photodiodes are then recombined using microwave circuits. This recombination process suppresses the undesired signals. The three fiber optic links proposed in this paper utilize these technologies of signal suppression and are summarized as follows:

Balanced Laser Harmonic Generation Link: Even and odd harmonics of RF frequencies generated by the laser diode nonlinearity are added and suppressed, respectively. One configuration consists of two laser diodes, two photodiodes, an out-of-phase divider, an in-phase combiner and two fibers. The other utilizes an optical combiner or an optical divider to reduce the number of fibers and optical devices from two to one, respectively. The primary objective of the link is to extend the link bandwidth which is beyond the relaxation oscillation limit of the laser diodes. The link can be applied to transmit the carrier reference signal which is used for the injection locking of local oscillator [5] or the local oscillator power of frequency mixer [14].

Balanced Laser Mixing Link: The laser diode nonlinearity is utilized to up-/down-convert signal frequencies in the links. The link configurations not only suppress local frequencies but also add the converted frequencies from each laser diode. The links are composed of two laser diodes, one or two photodiodes, out-of-phase dividers, in-phase combiners, and one or two fibers. Two fibers and two photodiodes can be reduced to one, respectively, by connecting an optical combiner. The objective of the laser mixing link is to eliminate electrical mixers in the optical receiver (In [14], the optical receiver is written as the sub-central terminal). This makes it possible to configure the receiver compact and cost-effective. The balanced laser mixing link can realize more compact and inexpensive optical receiver hardware than conventional laser mixing links.

Image Cancellation Laser Mixing Link: The up-converted frequencies, e.g., upper sideband and lower sideband frequencies are obtained separately from each output port. The link is composed of two laser diodes, two photodiodes, an out-of-phase divider, two in-phase combiners, two 90° hybrid circuits, and two fibers. The objective of the image cancellation laser mixing link is the same as that of the balanced laser mixing link.

The fundamental behavior of these configurations is

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discussed and their basic performance experimentally investigated at microwave frequency bands using commercially available optical devices.

Link Analysis

To describe the basic idea of the proposed fiber optic links, several equations have been derived in this section. The intensity modulated light output of the laser diode is generally written as [1]

$$P = P_0 * [1 + m * \cos(\omega t)] \tag{1}$$

where P_0 is the average light output, m is the optical intensity modulation index and ω is the modulation RF angular frequency. If the RF signal is split by the out-of-phase divider and supplied to each laser diode, the light output P_1 and P_2 from each diode is written as

$$P_1 = P_{01} * [1 + m_1 * \cos(\omega_1 t)] \tag{2}$$

$$P_2 = P_{02} * [1 + m_2 * \cos(\omega_1 t + \pi)] \tag{3}$$

where P_{01} and P_{02} are the average light outputs, m_1 and m_2 are the optical intensity modulation indices. The output of large-signal modulated laser diodes is expressed as [15]

$$\begin{aligned} P_1 &= P_{01} * [1 + m_1 * \cos(\omega_1 t) \\ &\quad + A_2 * \{m_1 * \cos(\omega_1 t)\}^2 \\ &\quad + A_3 * \{m_1 * \cos(\omega_1 t)\}^3 + \cdots] \\ &= P_{01} * [1 + m_1 * \cos(\omega_1 t) \\ &\quad + A_2 * \{m_1^2 * \cos(2\omega_1 t)\} \\ &\quad + A_3 * \{m_1^3 * \cos(3\omega_1 t)\} + \cdots] \end{aligned} \tag{4}$$

$$\begin{aligned} P_2 &= P_{02} * [1 + m_2 * \cos(\omega_1 t + \pi) \\ &\quad + B_2 * \{m_2 * \cos(\omega_1 t + \pi)\}^2 \\ &\quad + B_3 * \{m_2 * \cos(\omega_1 t + \pi)\}^3 + \cdots] \\ &= P_{02} * [1 + m_2 * \cos(\omega_1 t + \pi) \\ &\quad + B_2 * \{m_2^2 * \cos(2\omega_1 t)\} \\ &\quad + B_3 * \{m_2^3 * \cos(3\omega_1 t + \pi)\} + \cdots]. \end{aligned} \tag{5}$$

If two optical signals are detected by photodiodes and combined by an in-phase combiner, and the amplitude coefficients are equal, the fundamental and odd harmonics are suppressed and even harmonics added, due to the out-of-phase and in-phase relationship, respectively. Thus, both high frequency transmission above a relaxation oscillation frequency of laser diodes and suppression of undesired spurious frequencies is feasible using the laser diode nonlinearity and an RF-signal phase shift. A link with a function determined from (4) and (5) will be proposed using a combination of optical devices and microwave passive components.

If two modulation signals are superimposed onto the bias current of the laser diodes, the laser diodes can operate as an optical source and a frequency converter simultaneously [16]. The intensity modulated light output of the laser diode is expressed as

$$P = P_0 * [1 + m_1 * \cos(\omega_1 t) + m_2 * \cos(\omega_2 t)] \tag{6}$$

where ω_1 and ω_2 are the modulation angular frequencies. If the laser diode nonlinearity is used, (6) is expanded to

$$\begin{aligned} P &= P_0 * [1 + m_1 * \cos(\omega_1 t) + m_2 * \cos(\omega_2 t) \\ &\quad + A_2 * \{m_1 * \cos(\omega_1 t) + m_2 * \cos(\omega_2 t)\}^2 \\ &\quad + A_3 * \{m_1 * \cos(\omega_1 t) + m_2 * \cos(\omega_2 t)\}^3 + \cdots] \\ &= P_0 * [1 + m_1 * \cos(\omega_1 t) + m_2 * \cos(\omega_2 t) \\ &\quad + A_2/2 * m_1^2 * \cos(2\omega_1 t) \\ &\quad + A_2/2 * m_2^2 * \cos(2\omega_2 t) \\ &\quad + A_2 * m_1 m_2 * \cos(\omega_1 \pm \omega_2)t \\ &\quad + 3/4 * A_3 * m_1^2 m_2 * \cos(2\omega_1 \pm \omega_2)t \\ &\quad + 3/4 * A_3 * m_1 m_2^2 * \cos(\omega_1 \pm 2\omega_2)t + \cdots]. \end{aligned} \tag{7}$$

If both signal frequencies of ω_1 and ω_2 are divided out-of-phase and supplied to two laser diodes, the modulated light output of one diode is given by (7), while that of the other diode is expressed as

$$\begin{aligned} P' &= P_0' * [1 + m_1' * \cos(\omega_1 t + \pi) \\ &\quad + m_2' * \cos(\omega_2 t + \pi) + A_2' * m_1'^2 * \cos(2\omega_1 t) \\ &\quad + A_2'/2 * m_2'^2 * \cos(2\omega_2 t) \\ &\quad + A_2'/2 * m_1' m_2' * \cos(\omega_1 \pm \omega_2)t \\ &\quad + 3/4 * A_3' * m_1'^2 m_2' * \cos(2\omega_1 \pm \omega_2 + \pi)t \\ &\quad + 3/4 * A_3' * m_1' m_2'^2 \\ &\quad * \cos(\omega_1 \pm 2\omega_2 + \pi)t + \cdots]. \end{aligned} \tag{8}$$

If two optical signals, P and P', are combined in-phase, the fundamental frequencies of ω_1 and ω_2 are cancelled, and the sum and difference frequencies of $\omega_1 \pm \omega_2$ added. This balanced behavior is achieved using laser diode nonlinearities and microwave out-of-phase dividing functions. If one signal is divided by a 90° hybrid circuit, (8) is rewritten as

$$\begin{aligned} P'' &= P_0'' * [1 + m_1' * \cos(\omega_1 t + \pi) \\ &\quad + m_2' * \cos(\omega_2 t + \pi/2) \\ &\quad + A_2'/2 * m_1'^2 * \cos(2\omega_1 t) \\ &\quad + A_2'/2 * m_2'^2 * \cos(2\omega_2 t + \pi) \\ &\quad + A_2' * m_1' m_2' * \cos(\omega_1 + \omega_2 + 3\pi/2)t \\ &\quad + A_2' * m_1' m_2' * \cos(\omega_1 - \omega_2 + \pi/2)t \end{aligned}$$

$$+ 3/4 * A_3' * m_1'^2 m_2' * \cos(2\omega_1 + \omega_2 + \pi/2)t$$
$$+ 3/4 * A_3' * m_1'^2 m_2' * \cos(2\omega_1 - \omega_2 + 3\pi/2)t$$
$$+ 3/4 * A_3' * m_1' m_2'^2 * \cos(\omega_1 \pm 2\omega_2)t + \cdots]. \quad (9)$$

If two optical signals, P and P'', are combined by a 90° hybrid circuit, the upper and lower sideband signals are obtained separately from the output port of the 90° hybrid circuit. This operation is the same as that of the image cancel microwave mixer [17]. These functions are accomplished utilizing a combination of the laser diode nonlinearity and the phase shift of modulation frequencies.

Link Configurations

A. Balanced Laser Harmonic Generation Link

The configurations of the balanced laser harmonic generation link are shown in Fig. 1. The single-fiber links consist of an out-of-phase divider, one or two laser diodes, an optical combiner or divider, one or two photodiodes, and a fiber cable. The 180° RF signal phase shift is achieved using the out-of-phase divider which is connected to laser diodes in link A, while in link B the detected RF signals are combined by the out-of-phase combiner. Links C and D consist of two laser diodes, two photodiodes, an in-phase combiner, an out-of-phase divider and two fiber cables. The disadvantage of link B which uses only one laser diode is a 3-dB increase in link loss. The others could have the same link loss, if the laser diode and photodiode characteristics are equal.

As the basic behavior of the single-fiber link is the same as that of the twin-fiber link, the mechanism to cancel undesired signals is discussed below using the single-fiber link as an example for both. The input microwave signal is divided out-of-phase and then it modulates the laser diodes. Two intensity modulated optical signals which contain input RF frequency harmonics are combined by an optical combiner and detected by a photodiode. These two optical signals are expressed by (4) and (5), respectively. The fundamental and odd harmonics are cancelled due to a 180° phase difference. The even harmonics are added due to the in-phase relationship. The basic behavior of Fig. 1(b) and (d) is different from that of Fig. 1(a) and (c). The out-of-phase combiner is designed to give $n\pi$ phase shift to the fundamental ($n = 1$) and odd harmonics (n = odd number), and $m\pi$ phase shift to the even harmonics (m = even number). This circuit is configured simply using a quarter wavelength distributed transmission line whose length is designed at the fundamental frequency. Thus, in principle the detected microwave frequencies include only the even harmonics of the input RF frequency. Although the same idea was demonstrated using an optical interferometer [11], the link configuration proposed here utilizes microwave functional circuits such as out-of-phase dividers and combiners, and a couple of optical devices.

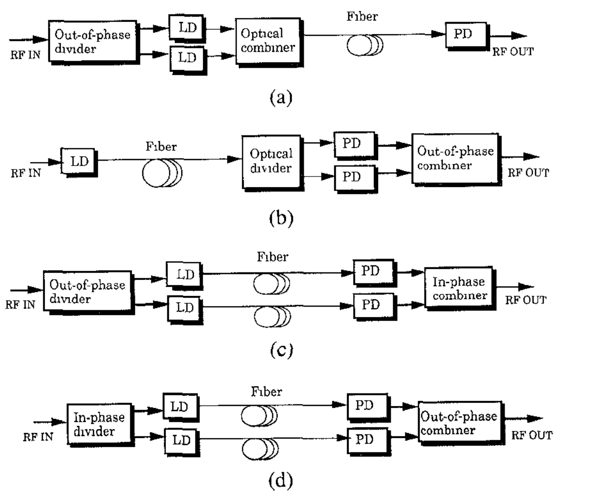

Fig. 1. Link configurations of balanced laser harmonic generation. (a) Single-fiber link configuration A using two laser diodes. (b) Single-fiber link configuration B using one laser diode. (c) Twin-fiber link configuration C. (d) Twin-fiber link configuration D.

B. Balanced Laser Mixing Link

Since the laser diode can operate as an optical source as well as a microwave frequency mixer, the laser diode mixer generates up-/down-converted signals and a local frequency, if two frequencies (local and IF/RF signals) are supplied. The output power level at the local frequency is larger than that of the upper and lower sideband signals if the IF signal level is low [14]. To suppress the local frequency, a microwave filter must be connected to the photodiode output. The balanced laser mixing link shown in Fig. 2 can eliminate local frequency without using filters. Two out-of-phase dividers and two in-phase combiners are required to supply the out-of-phase local frequencies (ω_1) and out-of-phase IF signals (ω_2) to the laser diodes. The light output of the laser diodes is expressed by (7) and (8). Since two detected local frequencies have a phase difference of 180°, they are cancelled at detector output. Thus in principle, the detected output does not include the local frequency, only the up-/down-converted signals.

C. Image Cancellation Laser Mixing Link

If the out-of-phase divider for the IF signal is replaced by a 90° hybrid circuit, the link can transmit the upper and lower sideband signals separately. The configuration of the image cancellation laser mixing link is shown in Fig. 3. The image cancellation configuration is based on the image cancel microwave mixer [17]. The local frequency (ω_1) is divided out-of-phase, while the IF signal (ω_2) is divided at a 90° phase difference. These divided frequencies are supplied to the laser diodes and then the frequency is mixed using the laser diode nonlinearity. The optical output power of the laser diodes is written in (7) and (9). Two photodiodes detect the modulated optical power, and the detected microwave frequencies are combined using the 90° hybrid circuit. The upper and lower sideband signals are obtained separately from each output port.

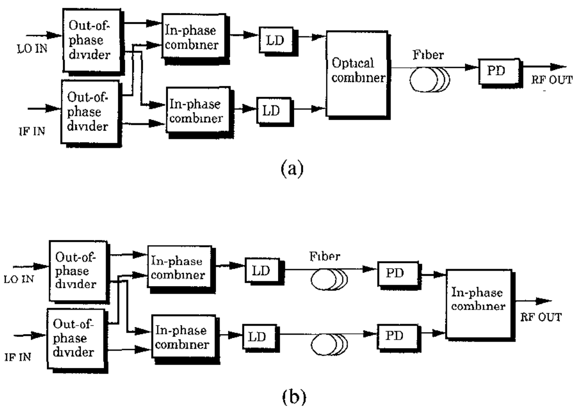

Fig 2. Link configuration of balanced laser mixing. (a) Single-fiber link configuration. (b) Twin-fiber link configuration.

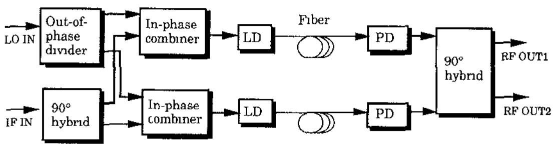

Fig. 3. Link configuration of image cancellation laser mixing.

Experimental Results

To verify the fundamental behavior of fiber optic links, the balanced laser harmonic generation link, the balanced laser mixing link and the image cancellation mixing link are experimentally investigated. Two InGaAsP laser diodes (Ortel 1515A) are used as harmonic generators and laser mixers. The first and second laser diodes have a threshold current of 19 mA and 15 mA and a *cw* output power of 1 mW at a forward bias current of 36 mA and 38 mA, respectively. The InGaAs *pin* photodiode (Ortel 2515A) has a 3 dB bandwidth of 10 GHz and a responsivity of 0.6 mA/mW. A conventional microwave 180° hybrid circuit is used as the out-of-phase divider. The optical coupler is used as the optical power combiner with a 3 dB optical power loss.

The detected harmonic levels of the balanced laser harmonic generation links (Fig. 1(a) and (c)) are shown in Figs. 4 and 5. The fundamental frequencies of the single- and twin-fiber links are 3 GHz and 2.5 GHz, respectively. The detected second, third and fourth harmonic levels of the single-fiber link at an RF input power level of 12 dBm are −35.8 dBm, −52 dBm and −47.8 dBm, respectively. As the detected fundamental frequency level is less than −80 dBm, the suppression ratio of the fundamental and second harmonic is greater than 44 dB. Frequency response of the single-fiber link is shown in Fig. 4(b). Although this link is balanced at the fundamental frequency of 3 GHz, the third-order suppression is worse than that of the fundamental because of the imbalance of components at the third-order frequency. Detected harmonic output of the twin-fiber link is shown Fig. 5(a). The second harmonic level is improved due to the absence of an optical combiner. Its value is −30.6 dBm at an input power level of 12 dBm. Since the detected power level of the fundamental is −76 dBm, the suppression ratio of the

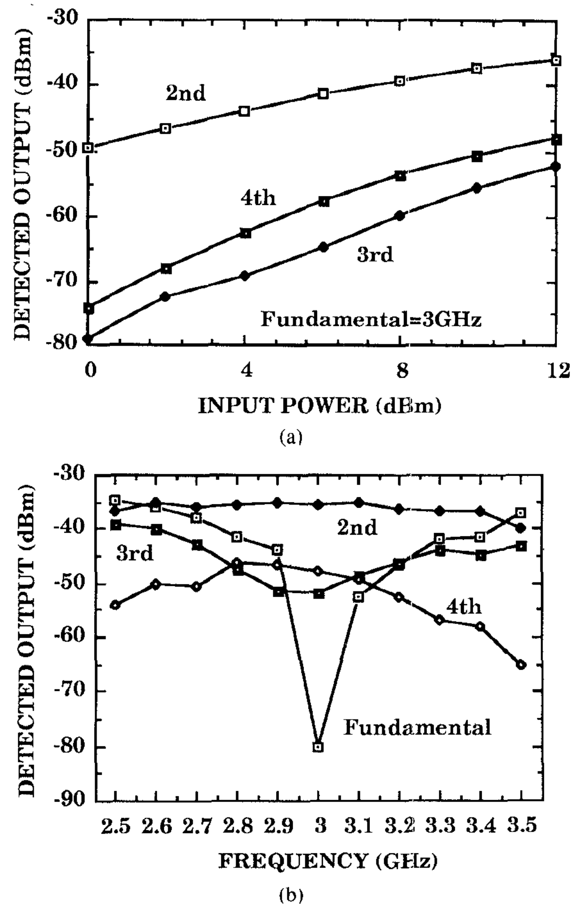

Fig. 4. Performance of single-fiber balanced laser harmonic generation link. The fundamental, 2nd harmonic, 3rd harmonic, and 4th harmonic frequencies are 3 GHz, 6 GHz, 9 GHz, and 12 GHz, respectively. (a) RF input power dependence. (b) Frequency response.

fundamental and second harmonic is 45.4 dB. Frequency responses of each harmonic are shown in Fig. 5(b). The odd harmonics are suppressed in the vicinity of the fundamental frequency of 2.5 GHz, as the even harmonic level increases. The detected harmonics spectrum of the single-fiber link at an input power of 12 dBm is shown in Fig. 6. The fundamental frequency of 3 GHz is suppressed and even harmonics added.

Balanced laser mixing link performance is shown in Fig. 7. The frequency responses of the upper and lower sideband frequencies as well as local frequency are shown in Fig. 7(a). The balanced mixing link is optimized at an IF frequency of 1.3 GHz. The detected power of the local frequency is −80.5 dBm, while that of the upper and lower sideband frequencies is −38.6 dBm and −39 dBm, respectively. A suppression ratio greater than 41.5 dB is obtained. Detected output power versus local input power of laser diodes is shown in Fig. 7(b). Since the two laser diodes used in the experiment have a different light output, the detected local power at photodiodes is strongly dependent on the local input power level of the laser diodes. The frequency spectrum of the balanced laser mixing link is shown in Fig. 7(c). The detected local power level is much lower than that of the converted frequencies.

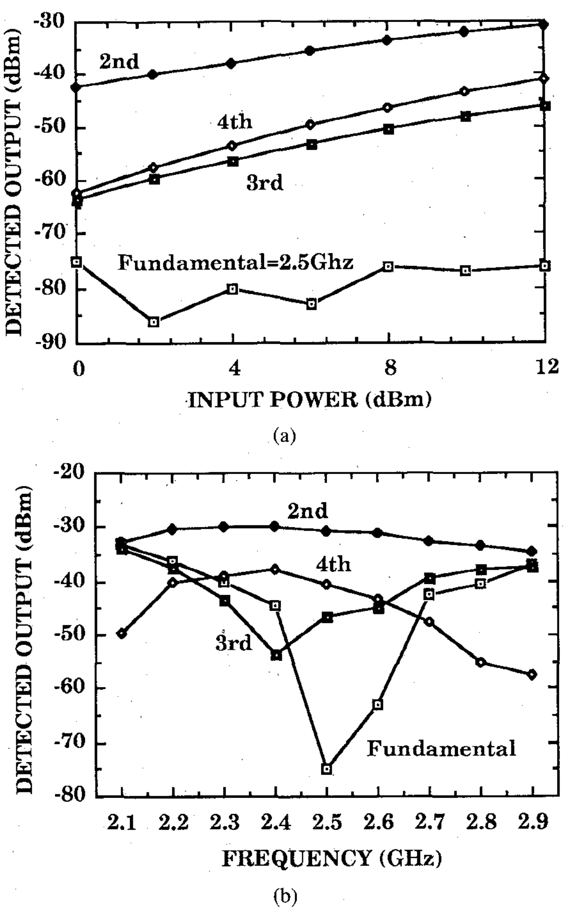

Fig. 5. Performance of twin-fiber balanced laser harmonic generation link. The fundamental, 2nd harmonic, 3rd harmonic, and 4th harmonic frequencies are 2.5 GHz, 5 GHz, 7.5 GHz, and 10 GHz, respectively. (a) RF input power dependence. (b) Frequency response.

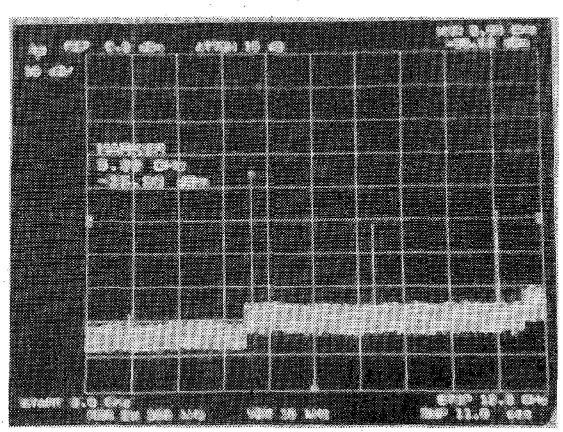

Fig. 6. Frequency spectrum of single-fiber balanced laser harmonic generation link. The input RF frequency is 3 GHz and the input power is 12 dBm. The start and stop frequencies are 2 GHz and 13 GHz, respectively. Horizontal axis: 1.1 GHz/div. Vertical axis: 10 dB/div.

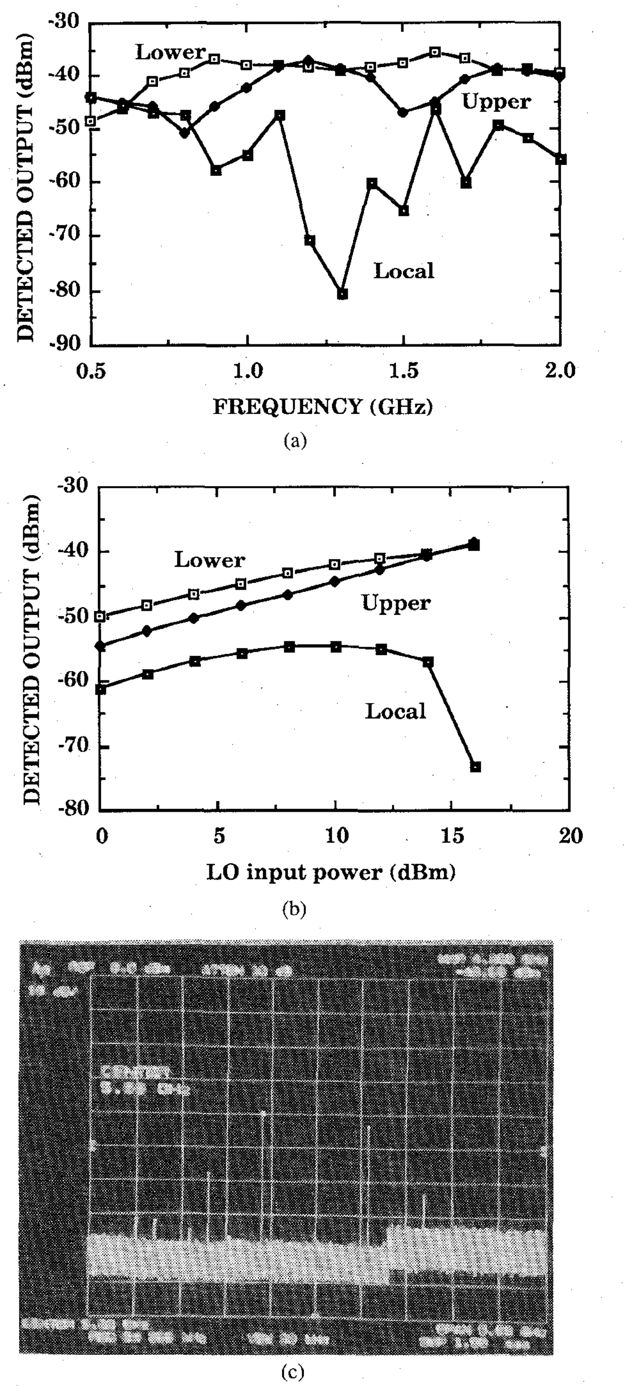

Fig. 7. Performance of balanced laser mixing link. (a) The local frequency is 6 GHz, and the local input power is 16 dBm. (b) The IF frequency is 1.3 GHz. (c) The local frequency is 5 GHz, and the IF frequency is 0.6 GHz. Horizontal axis: 0.5 GHz/div. Vertical axis: 10 dB/div. The center frequency of the photograph is 5 GHz.

The frequency response of the image cancellation laser mixing link is shown in Figs. 8(a) and (b). In Fig. 8(a), the upper sideband frequency corresponds to an RF frequency and the lower sideband frequency to an image frequency. On the other hand, in Fig. 8(b), the lower sideband frequency corresponds to an RF frequency and the upper sideband frequency to an image frequency. The bias condition of the two laser diodes is optimized at a local frequency of 8 GHz, a local input power level of 14 dBm, and an IF frequency of 1.25 GHz. An image rejection of 39.3 dB and 23.4 dB is achieved in Figs. 8(a) and (b), respectively. The detected up-converted (9 GHz) and down-converted (7 GHz) output power versus the IF (1 GHz) input power is shown in Fig. 8(c). The detected power is proportional to the input local and IF power level of the laser diodes.

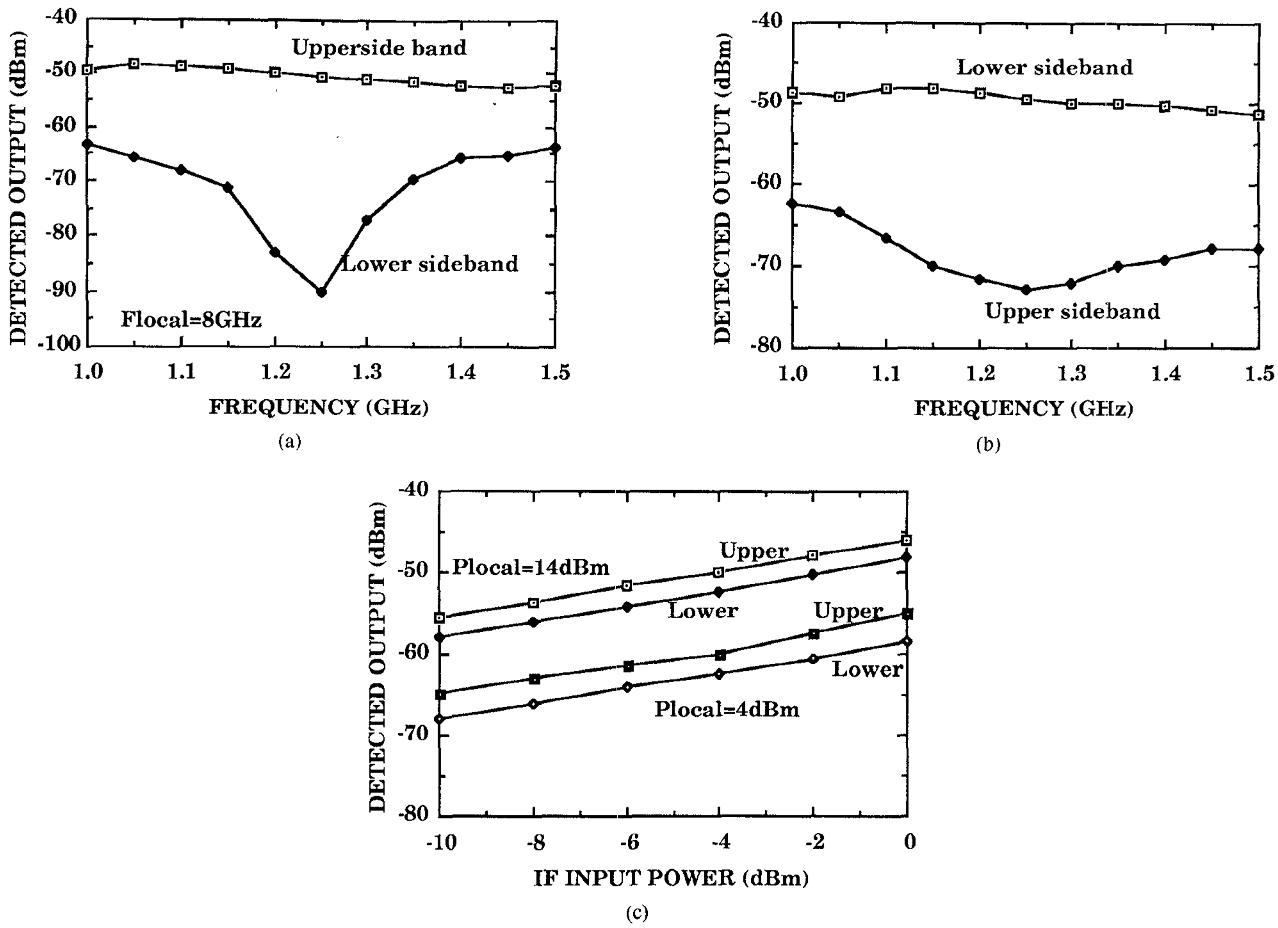

Fig. 8. Performance of image cancellation link. The local frequency is 8 GHz. (a) Frequency response of upper sideband. The local input power is 14 dBm. (b) Frequency response of lower sideband. (c) IF input power dependence. The local and IF frequencies are 8 GHz and 1 GHz, respectively.

TABLE I
EXPERIMENTAL RESULTS OF THREE FIBER OPTIC LINKS

	Balanced Laser Harmonic Generation Link Single-fiber Link	Balanced Laser Harmonic Generation Link Twin-fiber Link	Balanced Laser Mixing Twin-fiber Link	Image Cancellation Mixing Link
Fundamental frequency (RF)	3 GHz	2.5 GHz		
Local frequency (LO)			6 GHz	8 GHz
Intermediate frequency (IF)			1.3 GHz	1.25 GHz
Upper sideband frequency (Upper)			7.3 GHz	9.25 GH
Lower sideband frequency (Lower)			4.7 GHz	6 75 GHz
Suppression Ratio				
2nd harmonic/RF	>44 dB	45.4 dB		
3rd harmonic/RF	>28 dB	29.7 dB		
4th harmonic/RF	>33 dB	35 dB		
Upper/LO			41.9 dB	
Lower/LO			41.5 dB	
Upper/Lower				39.3 dB
Lower/Upper				23.4 dB

DISCUSSION

Signal suppression is feasible at microwave frequency bands using a combination of microwave functional circuits and optical devices. The proposed configurations use the phase relationship between the input signals of laser diodes and the output signals generated from laser diode nonlinearities to eliminate microwave filters. Experimental results of the three fiber optic links are summarized in Table I. The suppression ratio of the fundamental and second harmonic is greater than 40 dB at the balanced laser harmonic generation link. The balanced laser mixing link achieves a high suppression ratio (>40 dB) at the 6-GHz band. Therefore, these balanced configurations can operate as undesired signal suppression filters.

The frequency response deviation of laser diodes, and the amplitude and phase deviation of each microwave circuit causes an imbalance in the suppression ratio in the image cancellation link. However, despite the large number of circuit components in the optical links, a suppression ratio greater than 20 dB is obtained at the 8-GHz band. The disadvantage of these proposed links is the narrow transmission bandwidth. The frequency responses of each fiber optic link are shown in Figs. 4(b), 5(b), 7(b) 8(a) and (b). The bandwidth obtained is between 200 MHz and 400 MHz. Because of the limited bandwidth, these links are suitable for use as carrier transmission links which transmit an RF frequency or a local frequency [5], [14]. The imbalance of components will be significantly improved using monolithic integrated circuit technologies which make optical devices uniform [18] and also incorporate optical devices and microwave passive circuits.

Conclusion

Three fiber optic links have been proposed and experimentally investigated. The fundamental behavior of each link is described. Microwave functional components and optical devices are successfully combined and undesired spurious frequencies suppressed at microwave frequency bands. Although the experiment was done using the microwave frequency, the links can be expected to operate at millimeter-frequency bands by choosing ultra high-speed laser diodes and photodiodes, and millimeter-wave circuit components. The idea proposed in this paper can also be extended to photodiode mixing links [14], [19], and this will be reported elsewhere [20].

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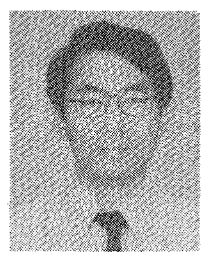

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