Fiber-Optic Microwave Transmission Using Harmonic Laser Mixing, Optoelectronic Mixing, and Optically Pumped Mixing

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Abstract —**This paper proposes three fiber-optic link configurations for use in microwave and millimeter-wave signal transmission. Harmonic laser mixing, optoelectronic mixing and optically pumped mixing are successfully utilized to achieve high carrier frequencies in fiber-optic links. The performance of harmonic laser diode mixers is experimentally investigated in the X band. The p-i-n photodiode is used as an optoelectronic microwave mixer and an optically pumped microwave mixer, and the microwave characteristics of these mixers are demonstrated. These three fiber-optic link configurations show promise in transmitting microwave and millimeter-wave frequencies.**

Introduction

WRIST-WATCH size portable TV telephone systems are under investigation for personal communication systems. These systems require wideband transmission capabilities, and very small and portable personal terminals. Because of the small equipment configuration, the portable terminal cannot generate high output power and thus, the maximum distance between the central terminal and the portable units is limited. Therefore, the number of sub-central terminals which connect the central terminal and portable terminals must be increased to service the numerous personal telephones. In order to provide wideband transmission capabilities and the necessary signal supply network for a number of sub-central terminals, fiber-optic links [1], [2] must be adopted for the wrist-watch telephone systems.

The optical transmission system under investigation utilizes a very large number of video subcarriers. Millimeter-wave frequencies are adequate to transmit such wideband video subcarriers. Microwave or millimeter-wave transmission by fiber-optic links has been attempted using external modulators [3], direct modulation [4], indirect subharmonic injection-locking techniques [5], [6], laser diode and photodiode nonlinearities [7], [8] and heterodyne techniques [9], [10]. The subcarriers can be used to intensity modulate a laser diode. Laser diodes with intensity modulation capability at these high frequencies are not generally available and are usually limited to operation below the relaxation oscillation frequency. However, it is possible using microwave harmonic generation and mixing to produce optical signals intensity modulated at microwave or millimeter-wave frequencies well above the relaxation oscillation frequency. In this paper, three fiber optic links utilizing a combination of the harmonic generation method [11], laser diode mixing [12], and optoelectronic mixing [13], [14], or optically pumped mixing [15], [16], are proposed. These three methods are successfully utilized to increase the output signal frequency at the central terminal or sub-central terminal. The combination of laser diode microwave harmonic generation [17] and laser mixing can increase the output signal frequency of both the central terminal and the sub-central terminal (laser diode mixing link A). The detected harmonics at the sub-central terminal can be used as the local oscillator input power for the optoelectronic mixer. The subharmonic mixing method can also be applied to the optoelectronic mixer. The combination of laser diode harmonic generation and subharmonic mixing makes it possible to increase the output signal frequency (photodiode mixing link B). The optically pumped mixer* investigated in this paper utilizes harmonics from laser diodes (photodiode mixing link C). Both mixer configurations have the advantage of frequency multiplication and of allowing sub-central receiver simplification. The three-fiber optic links proposed in this paper are summarized next.

Laser Diode Mixing Link (Link A): Frequency multiplication is achieved by harmonic laser diode mixing.

Photodiode Mixing Link (Link B): Frequency multiplication is achieved by laser diode harmonic generation and optoelectronic mixing as well as subharmonic optoelectronic mixing.

Photodiode Mixing Link (Link C): Frequency multiplication is achieved by laser diode harmonic generation and optically pumped mixing.

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*The optically pumped mixer defined in this paper is different from [15], [16]. Harmonics are generated by the laser diode and utilized as the local oscillator input power for the mixer. The detected harmonics behaves as if the local oscillator frequencies are pumped by the optical input power.

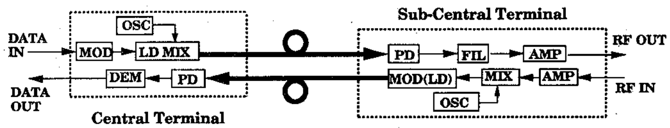


Fig. 1. Fiber-optic link configuration for microwave and millimeter-wave transmissions using harmonic laser diode mixing (laser diode mixing link—Link A).

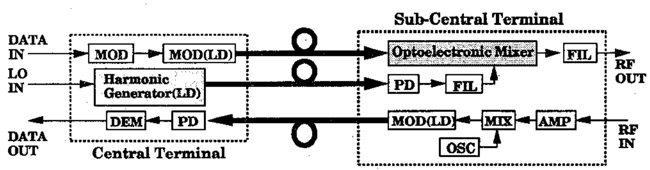


Fig. 2. Fiber-optic link configuration for microwave and millimeter-wave transmissions using harmonic generation and optoelectronic mixing/subharmonic optoelectronic mixing (photodiode mixing link—Link B).

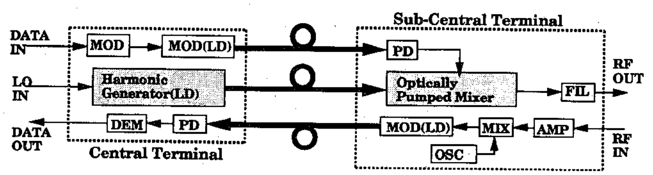


Fig. 3. Fiber-optic link configuration for microwave and millimeter-wave transmissions using harmonic generation and optically pumped mixing (photodiode mixing link—Link C).

Configuration of Fiber-Optic Links

The basic configurations of the fiber-optic links proposed in this paper are shown in Figs. 1–3. The functions of the central terminal are modulation/demodulation, and E/O–O/E conversion. The data signal is obtained by the electrical modulator, and then converted to the optical signal by the optical modulator (laser diode). The intensity modulated optical signal from the laser diode is transmitted to the sub-central terminal through the fiber-optic link and detected by the photodetector. The data signal is converted to the RF frequency in accordance with the following link architectures.

A. Harmonic Laser Diode Mixing Link—Link A

Although the laser diode can operate as an optical source and a microwave mixer simultaneously [12], the transmitted microwave frequency is limited by the bandwidth of the laser diodes. The use of harmonics permits the modulation capability of the laser diode to be extended beyond the relaxation oscillation frequency limit [11]. This allows better utilization of the fiber optic link bandwidth capability. The fiber-optic link shown in Fig. 1 exploits both laser diode harmonics and laser diode mixing, i.e., laser diode nonlinearities. The baseband signal is converted to the data signal and supplied to the laser diode mixer. The laser diode is biased to produce high harmonic levels. The harmonics are used as the laser local oscillator power for the laser mixer. The data signal and microwave harmonics are mixed in the laser diode. The intensity modulated optical signal from the laser diode contains the upconverted and down-converted signals as well as microwave harmonics. These signals are transmitted to the sub-central terminal and detected by the photodiode. The desired frequency is selected by the microwave filter. The frequency multiplication factor is determined from the laser diode harmonic order. The relationship between the output frequency f_s of the sub-central terminal and the laser local oscillation frequency f_l is expressed as

$$f_s = M_l \times f_l \pm f_d \quad (1)$$

where M_l is the frequency multiplication factor of the laser diode and f_d is the data signal frequency. To increase the output frequency of the sub-central terminal, a laser diode with a high relaxation oscillation frequency must be used [7]. The received RF signals at the sub-central terminal are amplified, then are converted to the intermediate frequency which can drive the optical modulators. The optically modulated signal is transmitted to the central terminal and then detected by the photodiode.

B. Photodiode Mixing Link—Link B

The fiber optic link using harmonic generation and optoelectronic mixing is shown in Fig. 2. The mixer local oscillator power for the optoelectronic mixer is obtained from the harmonic generator in the central terminal. The amplitude of the harmonics is optimized using the bias condition of the laser diode, the input laser local oscillator power level and laser local oscillator frequencies [11]. The received harmonics are detected by the photodiode and the desired frequency is selected by the microwave filter. The data signal is transmitted by another fiber cable and supplied into the optoelectronic mixer, then mixed with the mixer local oscillator power. The up- or down-converted signals are obtained from photodiode nonlinearities. Since the photodiode mixing efficiency strongly depends on the bias condition of the photodiodes [8], the photodiode bias voltage must be approximately zero. The output frequency is determined from the mixer local oscillator frequency and the data signal frequency. More explicitly, the relationship between the output frequency f_s of the sub-central terminal and the mixer local oscillator frequency f_l is expressed as

$$f_s = M_l \times M_m \times f_l \pm f_d \quad (2)$$

where M_m is the frequency multiplication factor of the optoelectronic mixer. $M_m = 1$ corresponds to fundamental optoelectronic mixing and $M_m > 1$ corresponds to subharmonic optoelectronic mixing.

C. Photodiode Mixing Link—Link C

In Fig. 3, it is the optically pumped mixer rather than the optoelectronic mixer that is used for generation of microwave signals. Harmonics generated from the laser diode are detected by the mixer and used as mixer local

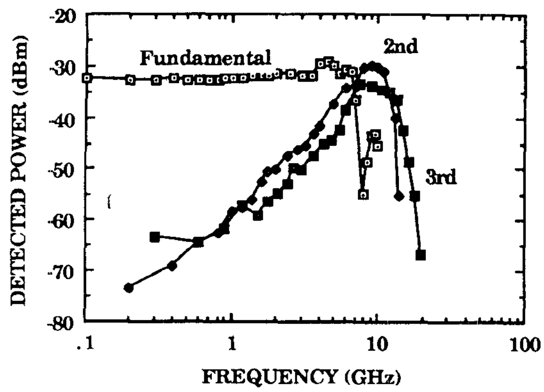


Fig. 4. Frequency response of laser diode (laser local oscillator input power = 10 dBm, laser diode bias current = 35 mA).

oscillator input power. The data signal is detected by the photodetector and supplied into the optically pumped mixer, then mixed with mixer local oscillator power. The up- or down-converted signals are obtained by photodiode nonlinearities. The relationship between the output frequency f_s of the sub-central terminal and the mixer local oscillator frequency f_l is expressed as

$$f_s = M_l \times f_l \pm f_{\text{sub}}. \quad (3)$$

Equation (3) is the same as (1). However, the inherent nonlinearities of the photodiode are exploited in Link C.

Experiment Results

Three fiber-optic links are experimentally investigated. The harmonic laser mixing and harmonic modulation are accomplished with an InGaAsP laser diode (Ortel 1510A). The laser diode has a threshold current of 20 mA and an cw output power of 0.6 mW at a forward bias current of 50 mA. The laser diode's 3 dB electrical bandwidth is approximately 7 GHz at a bias current of 35 mA. The InGaAs p-i-n photodiode (Lasertron QDEUHS-035) used as the mixer has a 3-dB bandwidth of 10 GHz and a responsivity of 0.5 A/W. In the laser diode mixing experiment, a microwave power divider was used to combine the laser local oscillator power and data signal frequency. The microwave 3-dB hybrid was used to separate the mixer local oscillator/data signal input power and the upconverted/down-converted output signals of the optoelectronic mixer and the optically pumped mixer. To compare the characteristics of three fiber-optic links, the local oscillator frequency of the laser diode is fixed at 4 GHz, and the data signal frequency at 0.9 GHz.

The nonlinear frequency response of the laser diode is shown in Fig. 4. The modulated optical power is detected by the photodiode. The harmonic level is optimized by adjusting the modulation frequencies and the bias current of the laser diode. The link loss of the 2nd harmonic at 8 GHz is 40.4 dB, while that of the 3rd harmonic at 12 GHz is 45.2 dB, both measured with laser local oscillator input power equal to 10 dBm, and at a laser diode bias current of 35 mA. The significant link loss reduction of the harmonics is achieved under the large-signal modula-

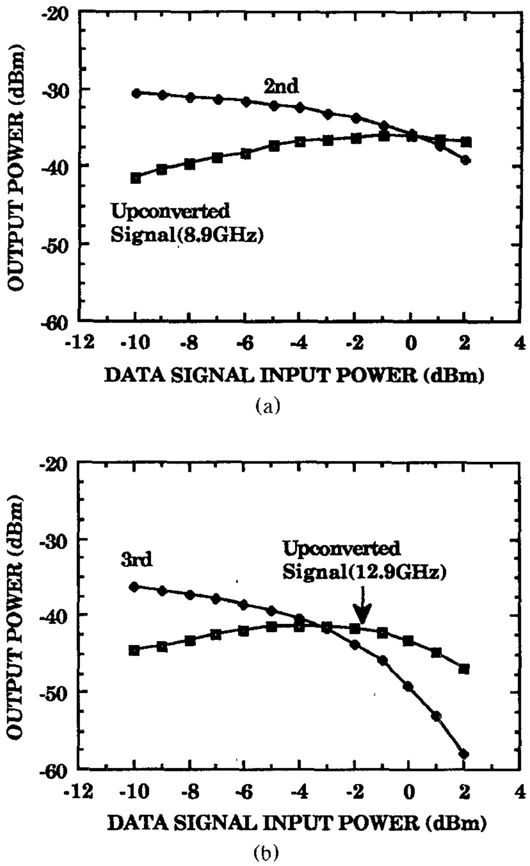
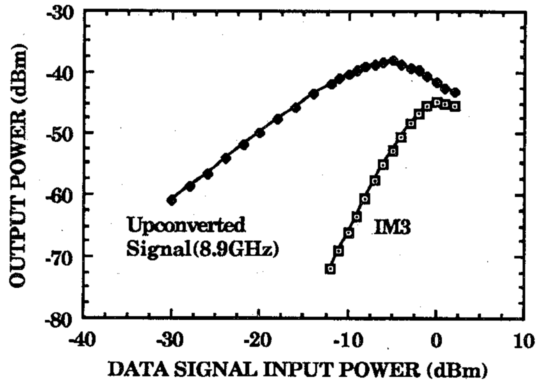


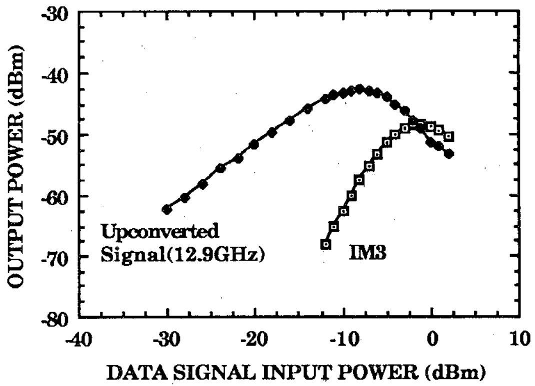
Fig. 5. Output power of harmonic laser mixer (laser local oscillator frequency = 4 GHz; laser local oscillator input power = 10 dBm; laser diode bias current = 35 mA; data signal frequency = 0.9 GHz). (a) Second harmonic response. (b) Third harmonic response.

tion close to the relaxation oscillation frequency [17]. The performance of the harmonic laser diode mixer is shown in Fig. 5. Fig. 5(a) shows the output power of the 2nd harmonic (8 GHz) and the upconverted signal (8.9 GHz). The maximum signal output power is −36.1 dBm at a signal input power of 0 dBm, and the minimum signal link loss of 31.4 dB is achieved at a signal input power less than −10 dBm. Since the link loss of the 0.9-GHz signal is 42.5 dB, a conversion gain of 11.1 dB from the 0.9-GHz signal to the 8.9-GHz upconverted signal is obtained. Fig. 5(b) shows the output power of the 3rd harmonic (12 GHz) and the upconverted signal (12.9 GHz). Due to the reduction of the 3rd harmonic level as shown in Fig. 4, the output power of the upconverted signal decreases. However, a conversion gain of 7.9 dB from the 0.9-GHz signal to the 12.9-GHz upconverted signal is obtained. The maximum output power is −41.3 dBm at a signal input power of −4 dBm, and the minimum link loss of 34.6 dB is achieved.

Another important parameter of the harmonic laser diode mixer is the third-order intermodulation product (IM3) [18], [19]. The IM3 of the harmonic laser diode mixer is experimentally evaluated. Fig. 6 shows the output power of the upconverted signal and IM3. Two equal-amplitude signals at 0.9 GHz and 0.91 GHz are used to

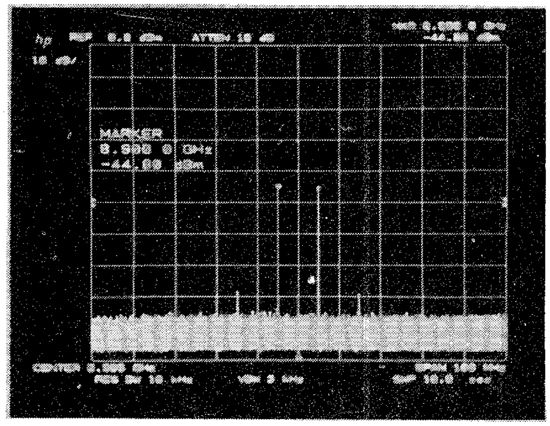


(a)

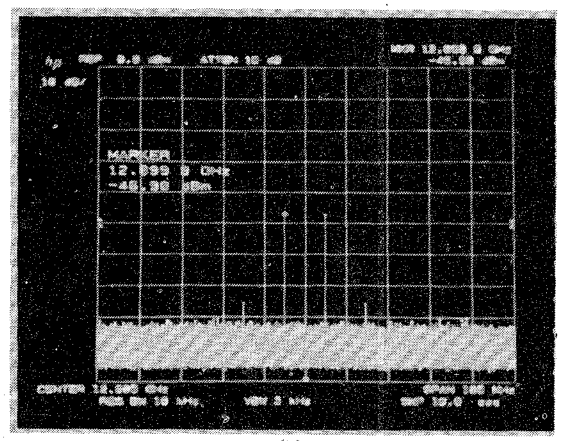


(b)

Fig. 6. Intermodulation product of harmonic laser mixer (laser local oscillator frequency = 4 GHz; laser local oscillator input power = 12 dBm. Laser diode bias current = 35 mA; data signal frequency = 0.9 GHz and 0.91 GHz). (a) Second harmonic response. (b) Third harmonic response.



(a)



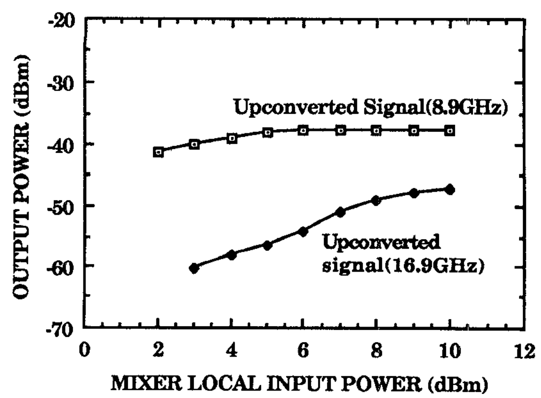
(b)

Fig. 7. Spectrum of intermodulation product (laser local oscillator frequency = 4 GHz; laser local oscillator input power = 12 dBm; laser diode bias current = 35 mA; data signal frequency = 0.9 GHz and 0.91 GHz; data signal input power = −15 dBm). (a) Second harmonic response. (b) Third harmonic response.

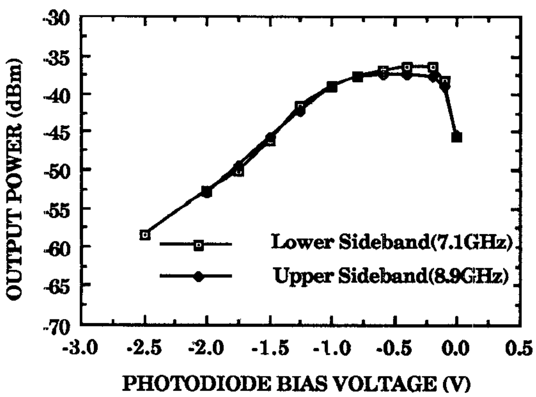
examine IM3 at 9.89 GHz and 9.92 GHz for the 2nd harmonic, and at 12.89 GHz and 12.92 GHz for the 3rd harmonic. The power ratio of the upconverted signal and IM3 using the 2nd and 3rd harmonics is 30 dB and 24.8 dB, respectively, at a signal input power of −12 dBm. Although the ratio can be improved by reduction of the signal input power, IM3 deteriorates at higher order harmonics. Fig. 7 shows the photographs of IM3 at a signal input power of −15 dBm.

The output power of the optoelectronic mixer and subharmonic optoelectronic mixer is shown in Fig. 8. The data signal input power and the bias current of the laser diode are 13 dBm and 45 mA, respectively. The mixer local oscillator frequency is fixed at 8 GHz. Minimum conversion loss is achieved at the reverse bias voltage of 0.5 V, as shown in Fig. 8(b). The mixing efficiency is optimized when the bias voltage is approximately zero, because the mixer local oscillator power generates photodiode nonlinearities. An output power of 37.6 dBm is obtained at a mixer local input power of 7 dBm. This corresponds to a link loss of 50.6 dB. The intrinsic conversion loss of the mixer is estimated to be 8.1 dB because the link loss of the data signal at 0.9 GHz is 42.5 dB. Since the second order local harmonic is generated in the photodiode, the mixer can function as a subharmonic mixer. Fig. 8(a) also shows the characteristics of the subharmonic optoelectronic mixer. The second harmonic frequency of the mixer becomes 16 GHz. The link loss of the upconverted signal (16.9 GHz) is 60 dB, and the obtained output power is −47 dBm. The conversion loss of the subharmonic mixer is 17.5 dB. Fig. 9 shows the other experimental results of the subharmonic mixer. The link loss of the upconverted signal (12.9 GHz) is 51.7 dB at a mixer local oscillator input power of 13 dBm, and a mixer local oscillator frequency of 6 GHz. An output power of −37.7 dBm is obtained. The upconverted signal (17.1 GHz) generated by the 3rd order mixer local oscillator power (18 GHz) is observed in the experiment. The link loss is 63.7 dB and the output power is −49.7 dBm at a data signal input power of 14 dBm.

The signal output power and the bias voltage dependences of the optically pumped mixer are shown in Fig. 10. The 2nd harmonic at 8 GHz and the 3rd harmonic at 12 GHz are directly detected by the mixer and used as mixer local oscillator frequencies. The 0.9-GHz data signal is directly supplied to the mixer diode. The signal conversion loss of 47.7 dB and 57 dB is achieved at a local



(a)



(b)

Fig. 8. Performance of optoelectronic mixer (mixer local oscillator frequency = 8 GHz; data signal frequency = 0.9 GHz; data signal input power = 13 dBm; laser diode bias current = 45 mA). (a) Photodiode bias voltage = −0.5 V. (b) Mixer local oscillator input power = 8 dBm.

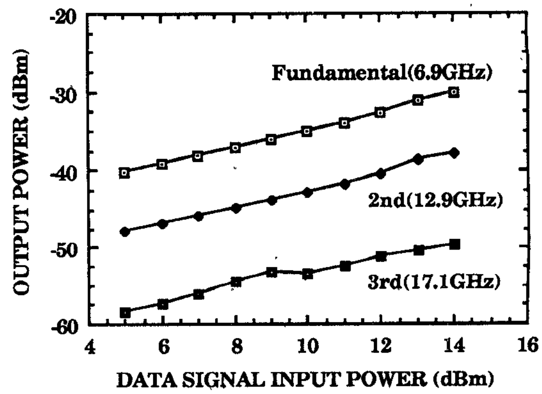


Fig. 9. Performance of subharmonic optoelectronic mixer (mixer local oscillator frequency = 6 GHz; mixer local oscillator input power = 13 dBm; data signal frequency = 0.9 GHz; laser diode bias current = 45 mA; photodiode bias voltage = −0.5 V).

frequency of 8 GHz and 12 GHz, respectively. The output power of the mixer is −40.1 dBm at 8.9 GHz, and −45.9 dBm at 12.9 GHz. Since the mixer local oscillator input power is dependent on the harmonic level generated in the laser diode, the signal conversion loss of the optically pumped mixer is larger than that of the optoelectronic mixer. In order to decrease the conversion loss, higher laser diode output power is required. The mixing efficiency is optimized at a bias voltage of approximately zero.

Discussion

The feasibility of frequency multiplication by harmonic laser mixing, optoelectronic mixing or optically pumped mixing is demonstrated in the X band. Table I summarizes and compares the experimental results of three fiber-optic link configurations. Link A has features high conversion gain, low link loss and simplification of the fiber-optic link architecture. Conversion gain and output power decrease as the harmonic order increases. To extend the effective bandwidth of Link A, laser diodes capable of generating high harmonic levels must be used. Although the laser diode mixing link has the advantage of reducing the number of microwave components at the central terminal and the number of fiber cables between the central terminal and the sub-central terminal, the dynamic range of the link is limited by low intermodulation product distortion.

The output power of the optoelectronic mixer is larger than that of the optically pumped mixer, because the local level for the optoelectronic mixer is much larger than that for the optically pumped mixer. The local input power of the optoelectronic mixer can be amplified by microwave amplifiers, while that of the optically pumped mixer is directly detected by the mixer itself. To increase the output power of the optically pumped mixer, high harmonic levels must be transmitted from the harmonic generator (laser diode) in the sub-central terminal. Since the photodiode in Link B is driven by the electrical local oscillator power, the harmonics of the mixer local oscillator frequency can be generated from photodiode nonlinearities. These harmonics are exploited to extend the fiber-optic link effective bandwidth. The photodiode mixing link configuration can eliminate microwave frequency converters in the sub-central terminal. This makes it possible to realize a small and cost-effective sub-central terminal. The photodiode mixing link can extend the link bandwidth up to millimeter-wave frequencies under the frequency limitation of opto-devices as well as of achieve simple and inexpensive equipment. Although Link B is composed of three fiber cables, each link can be optimized to have a wide dynamic range [20]. The photodiode mixing links realize signal conversions at the sub-central terminal, while the laser diode mixing link does so at the central terminal. The photodiode frequency conversion can eliminate the influence of the laser diode relative intensity noise. This helps to decrease the noise floor of the converted signals. The system noise figure is based on the operating condition of the laser diode. The relative intensity noise contributes to noise figure when the laser diode is operated near the relaxation oscillation frequency [21]. The photodiode mixing link is usually the least sensitive to laser noise because of the low frequency signal transmission.

TABLE I
COMPARISON OF THREE FIBER-OPTIC LINKS (DATA SIGNAL FREQUENCY = 0.9 GHz; LASER LOCAL OSCILLATOR FREQUENCY = 4 GHz; MIXER LOCAL OSCILLATOR FREQUENCY = 6 GHz AND 8 GHz)

Link	Upconverted Signal Frequency	Local Frequency	Output Power	Conversion Loss	Link Loss
Link A	8.9 GHz	4 GHz	−36.1 dBm	−11.1 dB	31.4 dB
	12.9 GHz	4 GHz	−41.3 dBm	−7.9 dB	34.6 dB
Link B	8.9 GHz	8 GHz	−37.6 dBm	8.1 dB	50.6 dB
	12.9 GHz*	6 GHz	−37.7 dBm	9.2 dB	51.7 dB
	16.9 GHz*	8 GHz	−47 dBm	17.5 dB	60 dB
Link C	8.9 GHz	4 GHz	−40.1 dBm	47.7 dB	—
	12.9 GHz	4 GHz	−45.9 dBm	57 dB	—

*Subharmonic optoelectronic mixing.

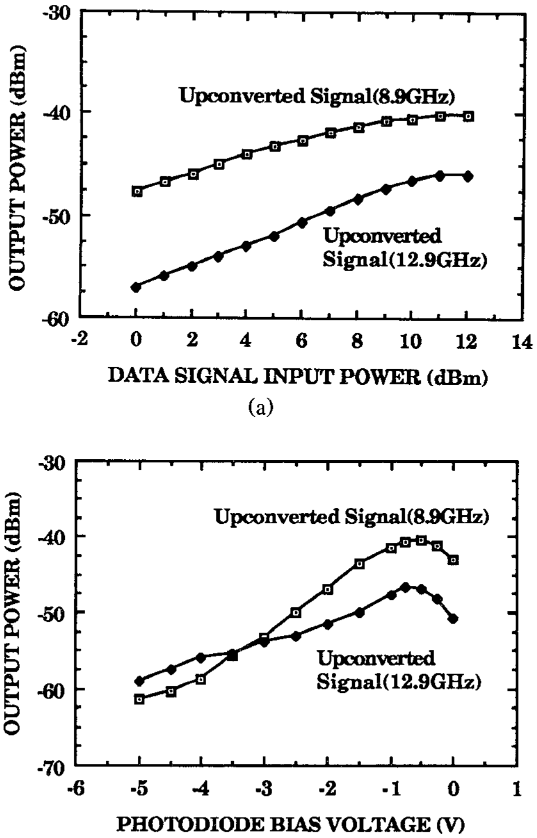


Fig. 10. Performance of optically pumped mixer (laser local oscillator frequency = 4 GHz; laser local oscillator input power = 15 dBm; laser diode bias current = 35 mA; data signal frequency = 0.9 GHz). (a) Photodiode bias voltage = −0.7 V. (b) Data signal input power = 15 dBm.

CONCLUSION

Three fiber-optic links, e.g., one laser diode mixing link and two photodiode mixing links, for microwave and millimeter-wave signal transmissions are proposed and experimentally investigated. The fundamental behavior of harmonic laser mixing, optoelectronic mixing and optically pumped mixing is described. The nonlinear characteristics of laser diodes and photodiodes are successfully exploited to achieve frequency multiplication in the fiber optic links. Although the experiment is done in the X band, the links can be expected to transmit millimeter-wave frequencies when ultra high-speed laser diodes and photodiodes are employed.

Fiber-optic distribution networks can be constructed using the fiber-optic links proposed in this paper. Each sub-central terminal forms microcell zones for communications between the central terminal and a number of wrist-watch size portable TV telephones. The cost-effective and small-sized sub-central terminals can be used in personal communication systems or phased array antenna systems.

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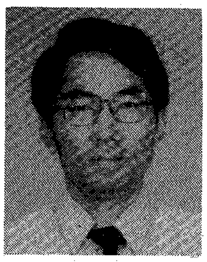

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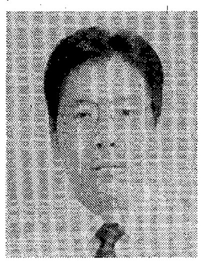

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In 1985 he joined Oyama International Communications Operations Center of Kokusai Denshin Denwa (KDD), Tochigi, Japan. From 1987 to 1991, he worked for ATR Optical and Radio Communications Research Laboratories, Kyoto, Japan, where he was engaged in research on active array antennas using optical technology. He is currently working on research of flat antennas for satellite communication systems in Applied Radio Systems Group of KDD R&D Laboratories, Saitama, Japan.

Mr. Kamiya is a member of the Institute of Electronics, Information and Communication Engineers of Japan.