Experimental Investigation of Fiber Optic Microwave Link with Monolithic Integrated Optoelectronic Mixing Receiver

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Abstract—**A fiber optic microwave link with a monolithic integrated optoelectronic mixing receiver (OEM) is demonstrated experimentally. The OEM consists of a GaAs metal semiconductor metal photodetector (MSM-PD) mixer and a MESFET transimpedance preamplifier. By modulating the bias of the MSM-PD with an electrical local oscillator, the information signals on an optical carrier are detected and converted to a desired electrical frequency simultaneously. Experimental results of a fiber optic microwave link with the OEM as a frequency up-converter are shown and the potential application of the OEM in fiber optic millimeter wave links is discussed.**

I. Introduction

TRANSMISSION of microwave and millimeter wave signals on optical fiber has been the subject of intensive research for the past few years, mainly due to large bandwidth and low loss of the optical fiber. The merging technologies of fiber optic and microwave/millimeter wave are expected to play an important role in future broadband distribution systems and local access networks. One example of this convergence is the subcarrier multiplexed (SCM) lightwave distribution system, in which a frequency division multiplexed signal set on optical carrier is detected and amplified by using a wideband optical receiver. An electronic mixer is then used to down-convert the signal outputs from the receiver to an intermediate frequency (IF). A major advantage of SCM systems compared with high speed baseband digital transmission is that existing RF and microwave electronics can be applied, and therefore high design flexibility and low cost are expected [1]–[3]. Another example is the fiber optic microwave and millimeter wave links for microcelluar communication systems, in which the amplitude of an optical carrier from a laser diode at a central station is intensity modulated by microwave subcarrier signals. After transmission via optical fibers, the modulated optical signals are detected and amplified by optical receivers at base stations. An electronic local oscillator (LO) and mixer are normally used to up-convert the signals from the optical receiver to a frequency for efficient radiation [4], [5].

The requirement for a wideband optical receiver is an impediment to low cost. The broadband optical receivers and following electrical mixers used in both systems can be simplified by using an optoelectronic mixing receiver (OEM), which performs the detection and frequency conversion simultaneously. The OEM has applications in SCM lightwave distribution systems, where it can be used to down-convert the microwave subcarrier frequencies to lower IF; and in a fiber radio system, where the OEM can be used to up-convert the subcarrier frequencies to higher frequencies for efficient radiation. The wideband receiver amplifier can then be replaced by a narrow bandwidth IF amplifier.

In fiber radio systems, one of the key issues is how to generate and transmit the microwave or millimeter wave subcarriers. Direct modulation of a laser diode up to millimeter wave frequency is usually impractical because of laser dynamics. Another limitation is the fiber dispersion which can be important at very high frequency. Optical generation of radio subcarriers, either with single or dual optical sources, have been reported [6], [7]. However, generation of such signals with sufficient stability and spectral purity is difficult and expensive. Furthermore, the photodetector is required to have sufficient bandwidth to respond to the high frequency subcarrier. With OEM conversion, the high frequency subcarriers are generated locally at base stations, instead of being generated at transmitter end and transmitted through fibers.

The OEM has been reported using optical devices, such as optical amplifier [8], semiconductor laser diode [9], and Mach-Zehnder modulator [10]. Photodiodes are attractive for OEM application due to their simple structure and easy implementation. OEM has been realized using photoconductor [11], avalanche photodiode [12], metal semiconductor metal photodetector (MSM-PD) [13]. and PIN photodetector [14]. Microwave transistors have also been demonstrated for OEM applications [15]–[17]. Recently we reported a monolithic integrated optoelectronic mixing receiver which consists of an interdigital MSM-PD and a transimpedance MESFET amplifier for both frequency down- and up-conversion applications [18], [19]. In this paper, we present details of an experimental investigation of a fiber optic microwave link with the monolithic integrated optoelectronic mixing receiver.

II. Operation of the OEM

The monolithic integrated optoelectronic mixing receiver consists of an interdigital MSM-PD with active area of $100\,\mu m \times 100\,\mu m$, finger width of 1 μm and spacing of 3 μm, respectively, and a preamplifier [19]. The operation of

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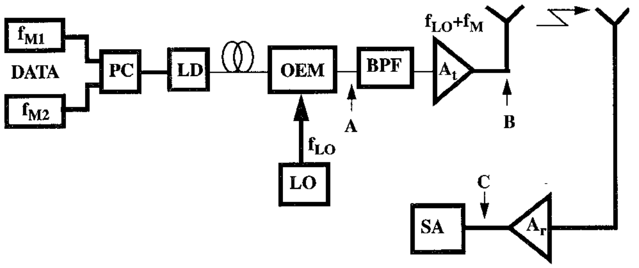

Fig. 1. Schematic diagram of a fiber optic microwave link with OEM. PC: power combiner; LD: laser diode OEM: optoelectronic mixing receiver; LO: local oscillator; BPF: bandpass filter; A_t: transmitting amplifier; A_r: receiving amplifier; SA: spectrum analyzer.

the OEM relies on the bias voltage dependent responsivity of the MSM-PD. The responsivity of the MSM-PD is a nonlinear function of the voltage applied. Assuming that the optical and electrical input signals to a biased MSM-PD are $P_M[1 + m\cos(2\pi f_M t)]$ and $V_{\rm LO}\cos(2\pi f_{\rm LO} t)$, where f_M is the modulation frequency, P_M the average power of the modulated optical carrier, m the optical modulation index, $f_{\rm LO}$ and $V_{\rm LO}$ the frequency and voltage of electrical local oscillator, $V_{\rm dc}$ the dc bias voltage for the MSM-PD, respectively, it can be easily shown that the signal current consists of $f_{\rm LO}, f_M, f_{\rm LO} \pm f_M$ and other higher order terms centered at $nf_{\rm LO}$, where n is the frequency multiplication factor. If $f_{\rm LO}$ is much higher than the overall bandwidth of the subcarrier multiplexed channels, all the higher order frequency components resulting from the nonlinearity of the MSM-PD will be out of the bandwidth of interest. Detailed analysis of OEM for a fiber optic microwave link application is given in [20].

III. Experimental Results and Discussion

The application of OEM in a fiber optic microwave link was experimentally investigated. The link configuration is shown in Fig. 1. The mixing receiver is mounted on an alumina substrate for testing. A GaAs/AlGaAs semiconductor laser diode emitting at wavelength of 780 nm is modulated by signals at frequency f_{M1} of 150 MHz and f_{M2} of 160 MHz for multichannel characterization. The signals are summed with a power combiner (PC). The power level of each of the modulation signals is set to be −10 dBm. The optical SCM carrier is incident on the MSM-PD via a short length of multimode optical fiber. The optical power from the fiber end is about 0.4 mW. The dc biased MSM-PD is modulated by a signal generator at frequency $f_{\rm LO}$ of 1.65 GHz and signal power of 0 dBm. The optical signals are detected and modulation frequencies are up-converted by the OEM. To suppress the local oscillator signal power, a bandpass filter with center frequency of 1.8 GHz and bandwidth of 50 MHz is inserted between the OEM and the following amplifier chain with total gain of about 40 dB. The amplified up-converted signals are fed into a discone type antenna. Discone antennas of the dimension used in this experiment match well over a band extending from about 0.9–2.0 GHz. The radiation pattern is nearly toroidal with a maximum gain in the polarization plane of 2 dBi. The distance between the transmitting and receiving antennas is 2 m. At receiving end, two amplifiers are used, each of which has a gain of 25 dB and a noise figure of 4.5 dB. A spectrum analyzer (SA) is used to measure the output of the link.

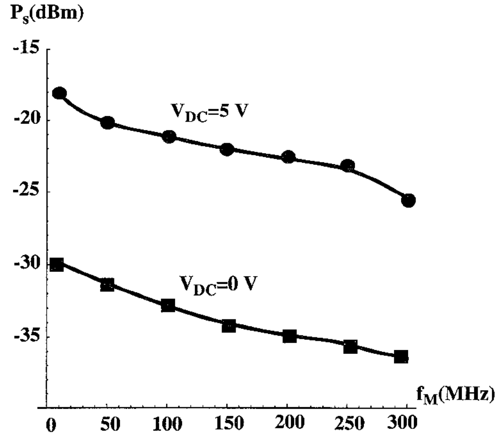

Fig. 2. Measured baseband signal power Pm of the OEM as function of modulation frequency f_m without LO modulation signal under different dc bias.

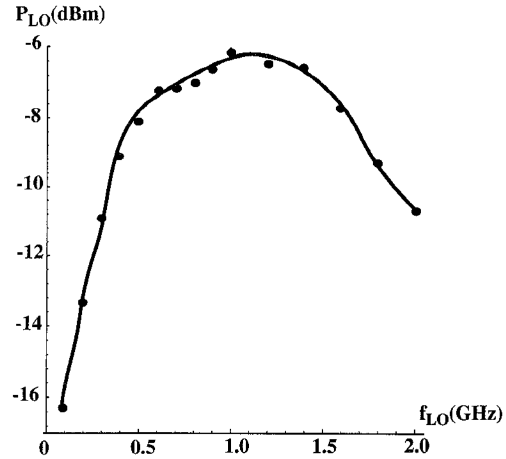

Fig. 3. Local oscillator signal power $P_{\rm LO}$ out of the OEM as function of frequency $f_{\rm LO}$.

Before the total link performance was evaluated, experimental characterization of OEM was carried out first. In Fig. 2, the measured frequency response of the receiver is shown for two different $V_{\rm dc}$. The measurement was taken at Point A in Fig. 1 with no local oscillator signals applied. By increasing $V_{\rm dc}$ from zero to 5 V, about 10 dB signal power increase is obtained. The 3 dB bandwidth of the MSM-PD is only about 150 MHz under both bias conditions. Even though the MSM-PD can not detect broadband optical signals, however, it can still be modulated at microwave frequency with electrical signal, and the mixing function can be performed.

In Fig. 3, the measured LO power out of the mixing receiver is shown as function of $f_{\rm LO}$. The mixing receiver offers a 3 dB tuning range of 1.4 GHz for LO modulation. The low frequency cutoff results from the bias tee inserted between the LO and OEM. The high frequency cutoff is due to the preamplifier. Because of the strong LO power at high frequency, the baseband signals carried by optical signal can be up-converted to a frequency range which is much

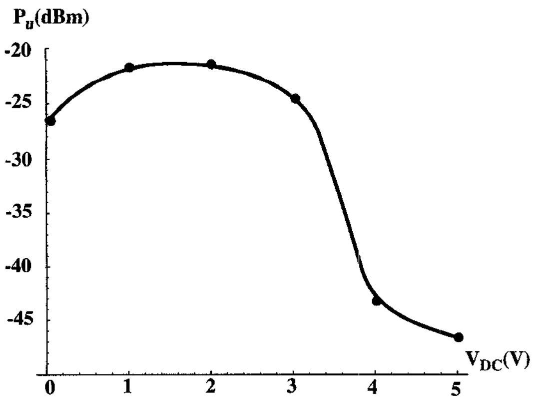

Fig. 4. Up-converted signal power P_u as function of MSM-PD dc bias voltage.

higher than that of the bandwidth of the OEM. This indicates the potential application of OEM for generating very high subcarrier frequency without the requirement of broadband photodetector.

When the OEM is used only to detect optical signals, a relatively large bias voltage is required to place the photodetector into high responsivity condition. In contrast, a low bias voltage is needed when the OEM performs frequency conversion simply because the differential responsivity of the MSM-PD is large at a low bias voltage. Fig. 4. shows the up-converted signal power as function of V_{dc}. For the OEM under investigation, the optimum V_{dc} is found to be 1.5 V for maximum up-converted signal power, due to the nonzero dc gate voltage of the input MESFET.

Fig. 5 shows the measured spectrum of up-converted signals and third order intermodulation products taken at Point B in Fig. 1. The frequencies of the signals are 1.80 and 1.81 GHz, respectively. It is seen that the subcarrier to intermodulation (IM) noise ratio is 43.6 dB. The measured subcarrier to IM noise ratio of the input modulation signals is 67.3 dB. The decrease of subcarrier to IM noise ratio results mainly from the laser diode nonlinearity. Even though the MSM-PD is modulated with a large signal from the LO, it can be easily shown that the nonlinearity of MSM-PD will not contribute to the IM noise in the system and only harmonic distortions are produced. Any harmonic distortions resulting from the large signal modulation of OEM are out of bandwidth of interest. Since the transmitting amplifiers operate at very low signal levels, their contribution to the system nonlinearity can be neglected. By reducing the input modulation signal power to -13 dBm, the reductions of subcarrier power and IM power are 3 and 9 dB, respectively, while the subcarrier to IM noise ratio is 43.5 dB. The spectra of up-converted signals and third order intermodulation products measured at Point C were found to be similar to that shown in Fig. 5, with a slight decrease of subcarrier to IM noise ratio which may result from the nonlinearity of the receiving amplifiers.

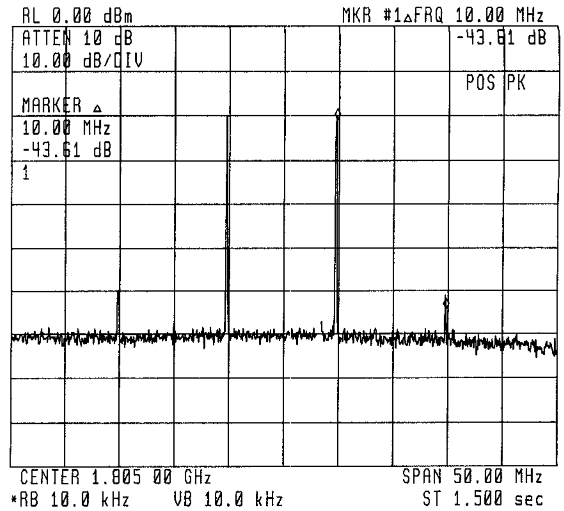

Fig. 5. Measured spectra of amplified up-converted signals and third order intermodulation products before fed into the transmitting antenna.

IV. Conclusion

In conclusion, we have demonstrated the application of a monolithic integrated optoelectronic up-converter in the fiber optic microwave link for simultaneous signal detection and subcarrier generation. The requirements for a high speed laser diode or an external optical modulator in the system are avoided. The nonlinearity of the laser diode used is the major source for the IM noise in the link, though the transmitting and receiving amplifiers also make contributions. Therefore, for transmitting multichannel signals with high quality, a highly linearized laser diode is needed. It has been demonstrated experimentally that up-conversion can be performed with MSM-PD whose response bandwidth is much lower than the subcarrier frequency. We anticipate that correct MSM-PD design and fabrication will provide devices capable of operating with subcarrier into the millimeter wave range. Systems using local generation of high frequency subcarrier are potentially less expensive than systems which attempt to propagate such subcarriers on fibers, or to generate them by optical heterodyne methods. Therefore the proposed system architecture offers a simple system design, low cost, and easy implementation.

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