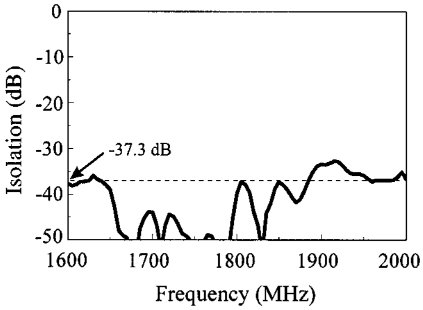

Figure 3 Measured isolation (S_{21}) between ports 1 and 2

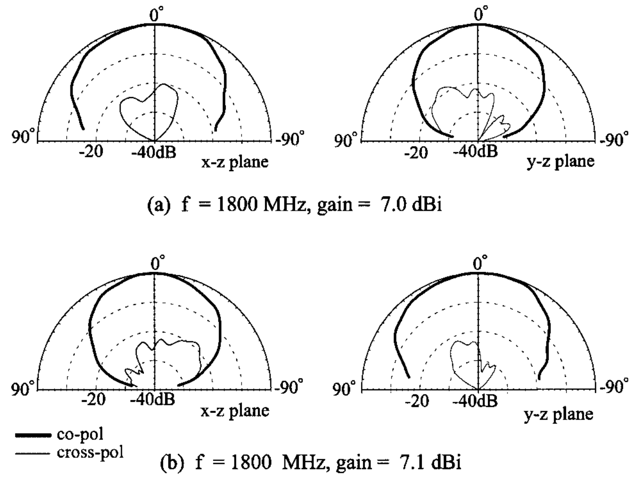

Figure 4 Measured radiation patterns at 1800 MHz. (a) Port 1 excitation. (b) Port 2 excitation

at two principal planes for port 1 and port 2 excitation at 1800 MHz. Good cross-polarization levels (about 20 dB) are observed for both linearly polarized waves, and the measured antenna gain is about 7.0 and 7.1 dBi for port 1 and port 2 excitation, respectively.

3. CONCLUSIONS

A compact dual-polarized aperture-coupled patch antenna with a cross-slot-loaded radiating patch and two carefully aligned H-shaped coupling slots has been described and investigated experimentally. The antenna studied shows good dual-polarized radiation characteristics over a wide operating bandwidth (about 10%) in the 1800 MHz band, and across the entire operating bandwidth, very good port decoupling (less than −37.3 dB) is obtained. This antenna is suitable for practical applications in a PCS mobile communication system.

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NONLINEARITY SUPPRESSION OF ELECTROABSORPTION MODULATOR THROUGH DUAL-PARALLEL MODULATION

Hyun-Do Jung,[1] Gyu-Woong Lee,[1] Sang-Kook Han,[1] and Woo-Young Choi[1]
[1] Department of Electrical and Computer Engineering
Yonsei University
134 Shinchon, Seodaemoon, Seoul, Korea

Received 10 October 2000

ABSTRACT: *A novel linearization method is proposed to increase the dynamic range of an electro-absorption modulator in suboctave bandwidth operation by exploiting the fact that the phase of third-order intermodulation distortion varies with the dc bias voltage. A reduction of 14 dB in IMD3 and a subsequent increase of the linear dynamic range were experimentally obtained.* © 2001 John Wiley & Sons, Inc. Microwave Opt Technol Lett 29: 2–5, 2001.

Key words: *electroabsorption modulator; dual-parallel modulation; linearization; intermodulation distortion (IMD); linear dynamic range*

1. INTRODUCTION

Recently, owing to an increase of mobile telecommunication subscribers and demands on a variety of high-quality services, the trend toward RF carrier frequency shows an increase to the μ/mm-wave frequency range. Related to this, an analog optical link with an extremely large bandwidth and low transmission loss has received attention as an efficient RF signal transmission link, both in wired and wireless communication systems. These links require a high linearity and a large dynamic range for better performance. However, direct modulation of a laser diode presents the problem of chirping, which limits high-frequency operation. So, a low-chirp high-speed external optical modulator needs to be used in spite of its inherent nonlinearity. An $LiNbO_3$ intensity modulator and an electroabsorption modulator (EAM) are good candidates for an external analog modulator. EAMs have many advantages, such as low driving voltage, small size, broad bandwidth, and monolithic integration with other components, in contrast to $LiNbO_3$ modulators. However, their inherent nonlinear transmission characteristics make it necessary to adopt complicated linearization techniques. Previously, linearization methods were reported, including RF current modulation [1], electronic predistortion [2, 3], feedforward compensation [4], distortion emulation, and reversal [5]. These methods require high-frequency operating electrical devices, and are mostly complicated.

In this letter, we propose a novel all-optical linearization technique to reduce the RF signal distortion caused by the nonlinear transfer curve of an electroabsorption modulator. A dual-parallel electroabsorption modulation scheme uses the nonlinearity of a sub-EA modulator in order to compensate that of the main EA modulator. The nonlinear distortion characteristic of the EAM is also analyzed. The validity of the proposed linearization process was confirmed by experimental demonstrations. In experiments, we used an electroabsorption modulator integrated laser (EML) instead of an EAM because the EAM is commercially unavailable. Using this scheme, an IMD3 reduction of 14 dB and a subsequent

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increase of the linear dynamic range of 7 dB were experimentally achieved.

2. NONLINEARITY OF EAM

The transfer function of the EA modulator [6] can be represented as follows, and is shown in Figure 1:

$$P_{\rm out}(V) = P_{\rm in}\exp[-\Gamma\alpha(V)L] = f(V) \qquad (1)$$

where $P_{\rm in}$ is the input optical power of LD, Γ is the confinement factor, α is the absorption coefficient, and L is the length of the EAM. Using a small-signal approximation, the harmonic and intermodulation distortions of the RF signals after passing the EAM can be evaluated by expanding its transfer function using a Taylor series for the dc bias voltage of interest. When the modulator is biased at dc voltage V_b and a modulating voltage V_m, the total applied voltage becomes $V = V_b + V_m$. Anticipating that $V_m \ll V_b$ for linear operation, we have considered Eq. (1) as a function of V, and it can be represented as follows:

$$\begin{aligned}\frac{P_{\rm out}}{P_{\rm in}}(V) &= f(V)\\ &= f(V_b) + \left.\frac{df}{dV}\right|_{V_b} V_m + \frac{1}{2!}\left.\frac{d^2f}{dV^2}\right|_{V_b} V_m^2 + \frac{1}{3!}\left.\frac{d^3f}{dV^3}\right|_{V_b} V_m^3\\ &\quad + \cdots = K_0 + K_1V_m + K_2V_m^2 + K_3V_m^3 + \cdots \qquad (2)\end{aligned}$$

where K_0, K_1, K_2, and K_3 are the Taylor series coefficients of the dc component, fundamental frequency, second-order distortion, and third-order distortion, respectively. From Eq. (2), we can see that the nonlinear distortion coefficients strongly depend on the slope variation of the transfer curve that is a function of the dc bias voltage. This slope variation of the transfer curve is shown in Figure 2. When a two-tone signal of f_1 and f_2 is applied, the magnitude of the received RF signals of f_1 and f_2, the composite second-order distortion (CSO) of $f_1 \pm f_2$, and the composite triple-beat distortion (CTB) of $2f_1 \pm f_2$ are important to determine the link performance [6]. In suboctave applications, the second-order nonlinearity falls out of the system passband, and can be filtered out by the electric circuit. So, the magnitude of the composite triple-beat distortion is the most important parameter for determining the link performance. Figure 3 shows the variation of the CSO and CTB magnitude for different dc bias voltages.

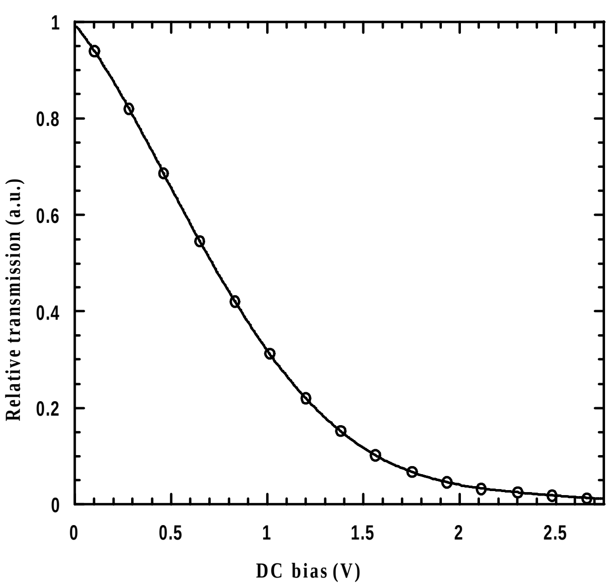


Figure 1 Transfer function of EAM

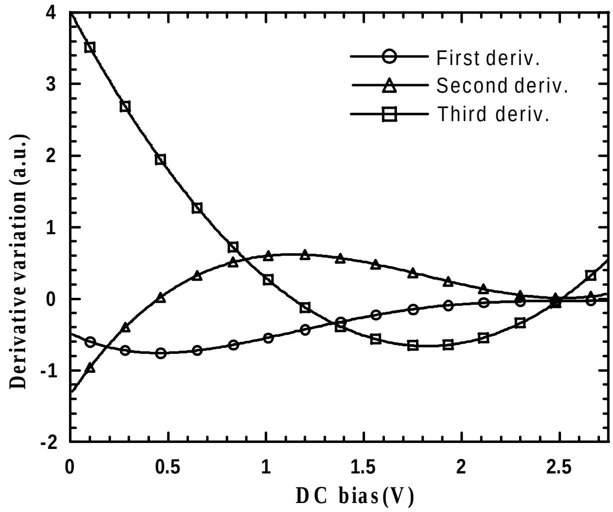


Figure 2 Slope variation of the transfer curve

3. LINEARIZATION

The proposed dual-parallel EA modulation scheme is implemented by two EMLs and a 3 dB optical coupler, as shown in Figure 4. As mentioned previously, the Taylor series coefficients strongly rely on the dc bias voltage. If we choose the dc bias position of the main (upper) and sub (lower) EAM properly, the spurious distortion RF signals imposed on the sub-EAM can have an opposite sign with respect to the spurious one of the main EAM from Eq. (2) and Figure 2. In view of the RF signal, two spurious signals are out of phase. The photodetector acts as an in-phase microwave combiner such that it coherently adds the detected RF signals. Two of the IMD3 signals are added destructively when they are π

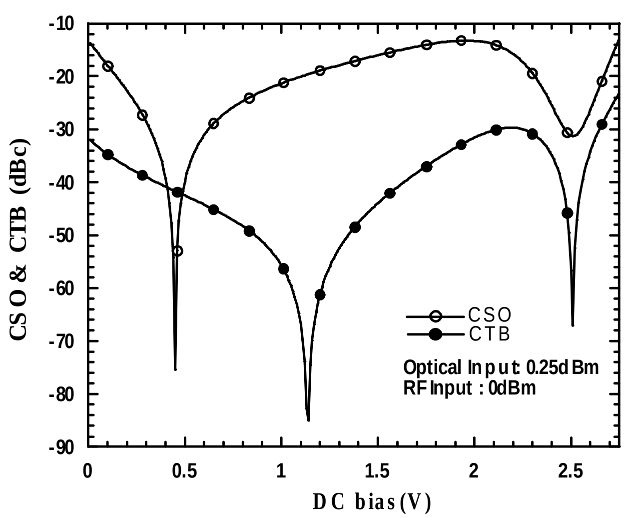


Figure 3 CSO and CTB in single EAM

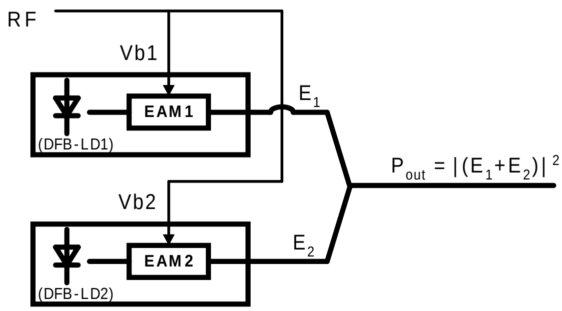


Figure 4 Schematic of dual-parallel EML modulation

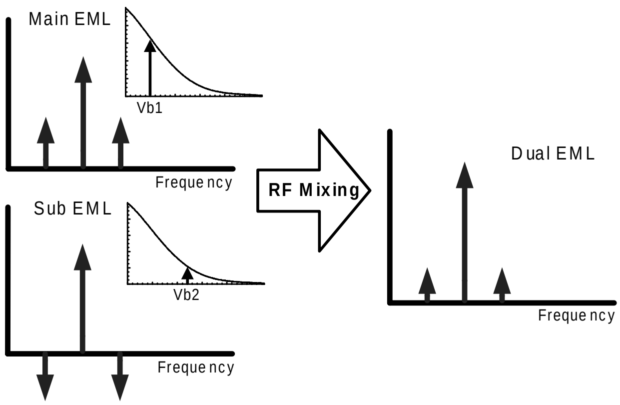


Figure 5 Conceptual representation of the dual-parallel modulation

out of phase. Then, nonlinear distortion compensation is realized. The conceptual representation of linearization is shown in Figure 5.

4. EXPERIMENTS

Figure 6 shows the experimental setup. The EML consists of an InGaAs/InGaAsP quantum-well electroabsorption (EA) modulator and a DFB laser. Each DFB LD operates at a different wavelength of 1562.7 nm, 1554.6 nm. A two-tone RF signal of 0.9 and 0.95 GHz is divided equally and applied to each EML. The dc bias voltage of two EMLs is controlled

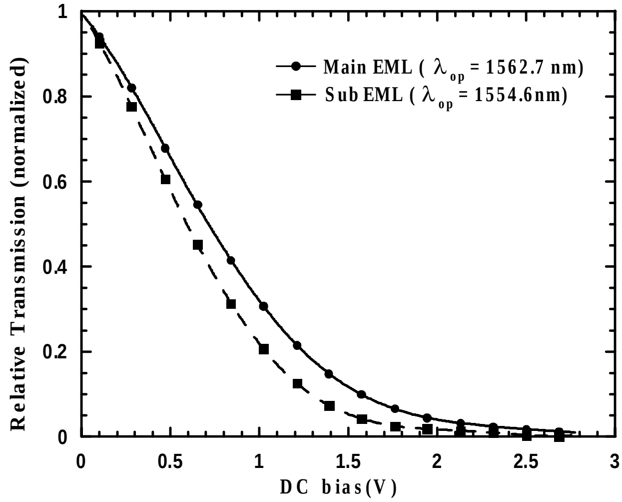


Figure 7 Measured transfer curve of two EMLs

separately. The modulated optical signals from each EML are injected into the OE converter via a 2×1 optical 3 dB coupler. The OE converter consists of the photodetector with a 0.6 A/W responsivity and the RF amplifier with a 20 dB gain. After photodetection, the fundamental and the nonlinear products are measured by an RF spectrum analyzer.

Figure 7 shows the measured optical output power of EMLs versus the dc bias voltage. We chose the EML emitting at 1562.7 nm as the main modulator. In order to find the rough bias condition for the reduction of the IMD3 of the main EML, we analyzed the third-derivative variation of transfer curves of the main and sub-EML. We found that the third-order distortion of the main EML and sub-EML has a reverse slope in the low-bias region (< 0.4 V) and in the high-bias region (> 1 V), respectively. Through careful bias control, maximum suppression of the IMD3 was obtained at 0.3 V (main) and 1.2 V (sub). It is thought that the phase difference of the IMD3 of the main and sub-EML becomes nearly 180° at this bias position.

Figure 8(a) represents the detected RF signal spectrum of the single EML at a dc bias of 0.3 V. At this bias position, the IMD3 was -36 dBc. By controlling the dc bias of the

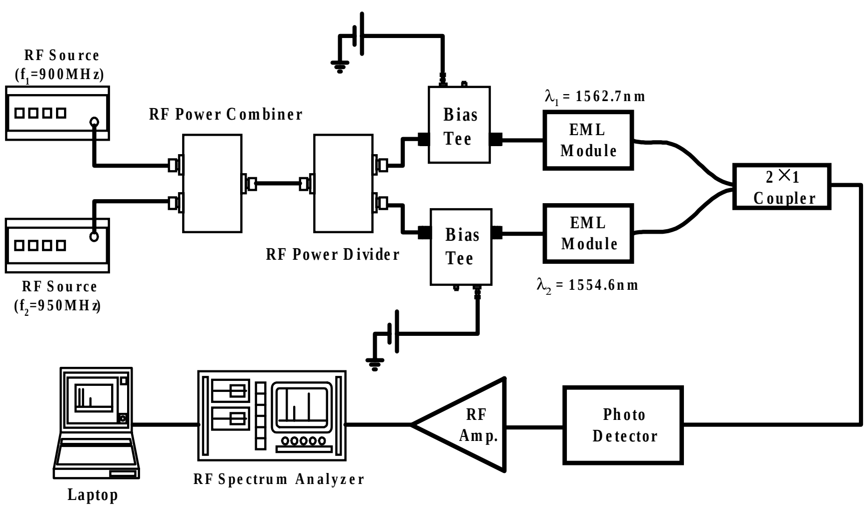
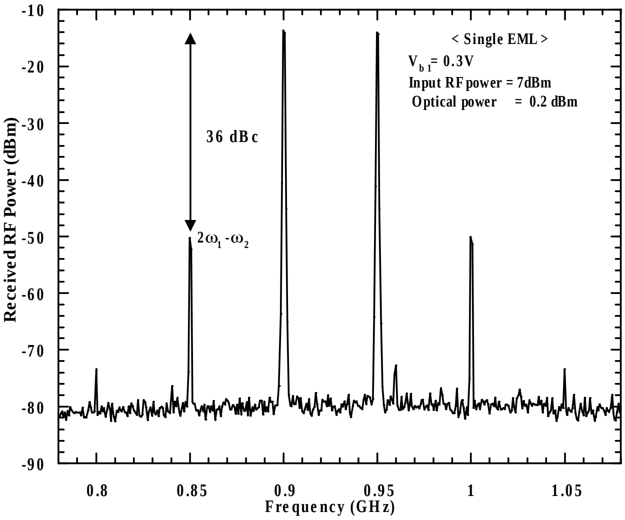
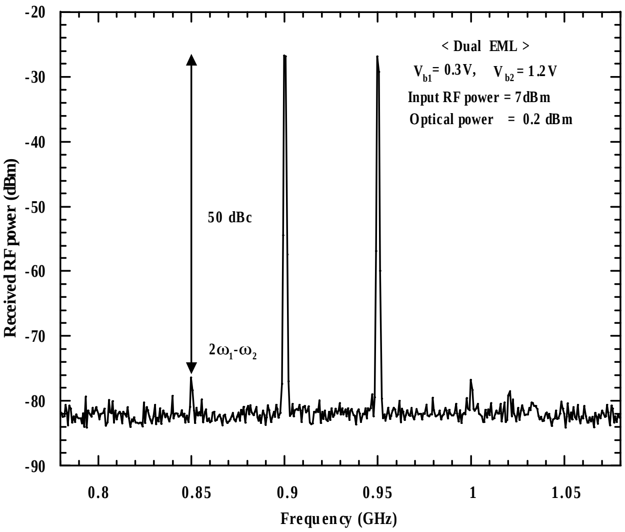


Figure 6 Experimental setup



(a)



(b)

Figure 8 Received RF spectrum. (a) Single EML. (b) Dual EML

sub-EML 14 dB, a reduction of the IMD3 to -50 dBc was obtained in the case of a dual-parallel scheme, as illustrated in Figure 8(b). However, the received RF power of the dual EML was reduced by nearly 10 dB compared to that of the single EML. It is thought that the cause of loss is the 3 dB RF divider and the 3 dB optical coupler. In these experiments, we expected a 6 dB loss of the fundamental signal due to both the coupler and divider. But the optical coupler had an extra loss of 3 dB. Thus, it seems that these losses and the extra connector loss contributed to a reduction of the fundamental signals. Figure 9 shows the received RF powers of the fundamental signals and the third-order intermodulation signals as a function of the input RF power for a single- and a dual-EML scheme. The single EML without linearization scheme showed a linear dynamic range (LDR) of 107 dB, which was increased to 114 dB with an average detected current of 0.54 mA and equivalent noise floor of -170.6 dBm/Hz. A 7 dB improvement of the dynamic range has been obtained, and further improvement is expected through the optimization of the dc bias positions.

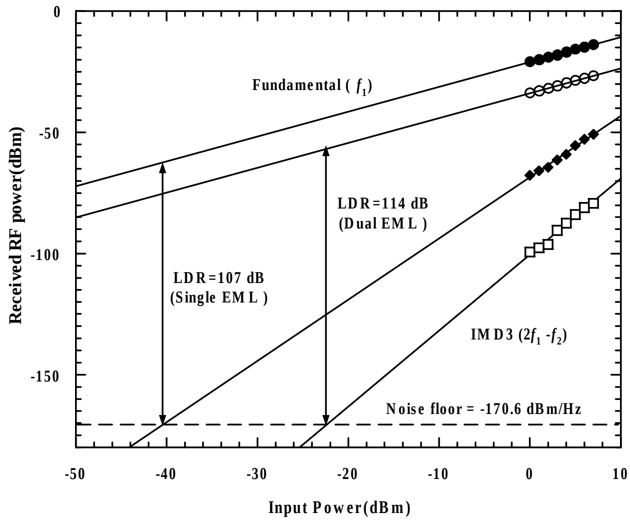


Figure 9 Measured LDR (filled: single EML, unfilled: dual EML)

5. CONCLUSION

In summary, we have proposed and experimentally demonstrated an all-optical dual-parallel EA modulation scheme. The only parameter that needs to be controlled is the dc bias voltage for suppressing the nonlinearity of the EML. By using the dc bias voltage of the main and sub-EML in an opposite slope in the derivative of the transfer curve of the EMLs, the third-order intermodulation products of the main EML could be reduced. In experiments, we focused on the verification of our scheme. For narrowband applications, a 14 dB reduction of the IMD3 and a 7 dB improvement of the LDR were obtained in experiments. Since the demonstrated linearization scheme is simple and robust, we believe that it is very useful for an efficient analog optical transmitter.

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