

Novel Electro-Optical Pre-distortion Technique and its Application in Externally Modulated CATV Transmission Systems

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Abstract

Conventional linearization techniques such as electrical pre-distortion or optical feedforward methods have been applied to Mach-Zehnder interferometer (MZI) modulators for CATV transmission systems. However, both methods can only ensure that the output of the MZI modulator meet the standard CATV requirements on composite second-order (CSO) and composite triple beat (CTB), but cannot guarantee a satisfactory end-to-end system linearity. In this paper, we propose and demonstrate a novel linearization technique, which can simultaneously suppress the nonlinear distortions (NLDs) generated in a transmission system and increase the received carrier-to-noise ratio (CNR). This technique is based on offsetting the MZI bias voltage from its inflection point. Both analytical and experimental results are presented.

I. INTRODUCTION

The sinusoidal light versus bias voltage (L-V) transfer curve of a LiNbO₃-based external modulator prevents a multichannel CATV system from obtaining a highly linear performance. Presently, however, external modulator-based transmitters are linear enough to transport > 80 channels of AM video signals because an electrical pre-distortion technique with two arrangements have been successfully used. The first arrangement is that the bias point of the external modulator is fixed at the inflection point of the sinusoidal L-V curve [1] so that second-order nonlinear distortions (NLDs) can be completely suppressed. The second arrangement is that a third- and/or fifth-order pre-distortion circuit is inserted between the modulating signal source and the external modulator, so that the major odd-order NLDs can be suppressed significantly. However, even when this highly linear optical transmitter is used in an optical fiber CATV system, the performance of the entire system can still exhibit high CSOs because many other NLD-generation mechanisms may exist. For examples, CSOs can be generated from optical receivers, semiconductor optical amplifiers (SOAs), linear optical fiber dispersions [2, 3], self-phase modulations [2, 3, 4], interferometric multiple reflections [5, 6], etc. Therefore, it may be preferred to design an optical transmitter that can provide a highly linear performance for the end-to-end system. In other words, the optical transmitter can itself generate certain levels of NLDs, in order to compensate the NLDs generated from the transmission system.

In this letter, we propose a novel pre-distortion technique in an external modulation system. This technique is used to compensate the frequency-independent CSO products generated from the transmission link. The basic idea of this technique is to shift the bias point of an external modulator from its inflection point so that transmitter-generated CSO products can be used to cancel those from the system. We experimentally demonstrate the feasibility of this technique by using a 1.3 μm -external modulator-based transmitter whose bias voltage is offset from the inflection point. The transmitter-generated CSOs can be used to compensate those generated from a 1.3 μm semiconductor optical amplifier.

II. OPERATION PRINCIPLE

The operation principle of the proposed technique is explained in this Section. We start with the static transfer characteristic of an MZI modulator given by

$$P_{\text{out}}(t) = \frac{P_{\text{in}}L_a}{2} \left[1 + \sin \left(\frac{\pi}{V_\pi} V(t) + \phi \right) \right] \quad (1)$$

where P_{out} is the output power of the MZI modulator, P_{in} is the input power of the MZI modulator, L_a is the insertion loss due to the MZI modulator, $V(t)$ is the modulating voltage, V_π is the half wave voltage of the MZI modulator (the voltage required to achieve 180° optical phase shift), and ϕ is static bias phase shift. Assume that the modulating voltage $V(t)$ is composed of multiple channels of CATV signals and a DC bias voltage V_b :

$$V(t) = \sum_{i=1}^N A \sin(\omega_i t + \theta_i) + V_b \quad (2)$$

where A is the amplitude and ω_i is the angular frequency of the i -th channel. By substituting Eq.(2) into Eq.(1), the AC output of the MZI modulator can be expanded as

$$\begin{aligned} & \frac{P_{\text{in}}L_a}{2} \cdot \sin \left[\frac{\pi}{V_\pi} V(t) + \phi \right] \\ &= \frac{P_{\text{in}}L_a}{2} \cdot \sin \left[\frac{\pi}{V_\pi} \left(\sum_{i=1}^N A \sin(\omega_i t + \theta_i) + V_b \right) + \phi \right] \\ &= \frac{P_{\text{in}}L_a}{2} \cdot \left\{ \sin \left(\frac{\pi}{V_\pi} V_b + \phi \right) \cos \left[\frac{\pi}{V_\pi} \sum_{i=1}^N A \sin(\omega_i t + \theta_i) \right] \right. \\ & \quad \left. + \cos \left(\frac{\pi}{V_\pi} V_b + \phi \right) \sin \left[\frac{\pi}{V_\pi} \sum_{i=1}^N A \sin(\omega_i t + \theta_i) \right] \right\} \end{aligned} \quad (3)$$

Let $\chi = \frac{\pi}{V_\pi} A$, we can use Bessel function expansions to obtain

$$\begin{aligned} & \sin \left[\frac{\pi}{V_\pi} \sum_{i=1}^N A \sin(\omega_i t + \theta_i) \right] \\ &= \left\{ \sum_{n_1=-\infty}^{\infty} \sum_{n_2=-\infty}^{\infty} \cdots \sum_{n_N=-\infty}^{\infty} J_{n_1}(\chi) J_{n_2}(\chi) \cdots J_{n_N}(\chi) \sin \left[n_1(\omega_1 t + \theta_1) + n_2(\omega_2 t + \theta_2) + \cdots + n_N(\omega_N t + \theta_N) \right] \right\} \end{aligned}$$

(4)

$$\begin{aligned} & \cos \left[\frac{\pi}{V_{\pi}} \sum_{i=1}^N A \sin(\omega_i t + \theta_i) \right] \\ & = \left\{ \sum_{n_1=-\infty}^{\infty} \sum_{n_2=-\infty}^{\infty} \cdots \sum_{n_N=-\infty}^{\infty} J_{n_1}(\chi) J_{n_2}(\chi) \cdots J_{n_N}(\chi) \cos \left[n_1(\omega_1 t + \theta_1) + n_2(\omega_2 t + \theta_2) + \cdots + n_N(\omega_N t + \theta_N) \right] \right\} \end{aligned} \quad (5)$$

where J_n is the n -th order Bessel function of the first kind. From Eqs.(3)-(5), we can obtain the fundamental carrier amplitude by letting $n_i=1, n_{j, j \neq i}=0$ to be

$$\frac{P_{in} L_a}{2} \cdot \left\{ 2 J_1(\chi) [J_0(\chi)]^{N-1} \cos \left(\frac{\pi}{V_{\pi}} V_b + \phi \right) \right\} \quad (6)$$

The amplitude of second-order intermodulation of the type $\omega_i + \omega_j$ is given by

$$\frac{P_{in} L_a}{2} \cdot \left\{ 2 [J_1(\chi)]^2 \cdot [J_0(\chi)]^{N-2} \cdot \sin \left(\frac{\pi}{V_{\pi}} V_b + \phi \right) \right\} \quad (7)$$

, and the amplitude of third-order intermodulation of the type $\omega_i + \omega_j - \omega_k$ is given by

$$\frac{P_{in} L_a}{2} \cdot \left\{ 2 [J_1(\chi)]^2 \cdot J_{-1}(\chi) \cdot [J_0(\chi)]^{N-3} \cdot \cos \left(\frac{\pi}{V_{\pi}} V_b + \phi \right) \right\} \quad (8)$$

Therefore, the power ratio of carrier to CSO is given by

$$\begin{aligned} \frac{C}{CSO} &= \frac{\left\{ 2 J_1(\chi) [J_0(\chi)]^{N-1} \right\}^2}{\left\{ 2 [J_1(\chi)]^2 [J_0(\chi)]^{N-2} \right\}^2 \cdot N_{CSO}} \cdot \cot^2 \left(\frac{\pi}{V_{\pi}} V_b + \phi \right) \\ &= \frac{1}{N_{CSO}} \cdot \left\{ \frac{J_0(\chi)}{J_1(\chi)} \right\}^2 \cdot \cot^2 \left(\frac{\pi}{V_{\pi}} V_b + \phi \right) \\ &\cong \frac{1}{N_{CSO}} \cdot \left(\frac{2}{\chi} \right)^2 \cdot \cot^2 \left(\frac{\pi}{V_{\pi}} V_b + \phi \right) \end{aligned} \quad (9)$$

where N_{CSO} is the product-count of CSO. The power ratio of carrier to CTB is given by

$$\begin{aligned} \frac{C}{CTB} &= \frac{\left\{ 2 J_1(\chi) [J_0(\chi)]^{N-1} \right\}^2}{\left\{ -2 [J_1(\chi)]^3 [J_0(\chi)]^{N-3} \right\}^2 \cdot N_{CTB}} \\ &= -\frac{1}{N_{CTB}} \cdot \left[\frac{J_0(\chi)}{J_1(\chi)} \right]^4 \\ &\cong -\frac{1}{N_{CTB}} \cdot \left(\frac{2}{\chi} \right)^4 \end{aligned} \quad (10)$$

where N_{CTB} is the product-count of CTB. From Eqs.(9) and (10), we can calculate the C/CSO and

C/CTB as a function of bias voltage offset (from inflection point) for any number of input carriers. Fig.1 is the result for single-tone input (with an optical modulation index or OMI equals to 0.6), and Fig.2 is the result for two-tone input (each with an OMI equals to 0.2). It is clear from Fig.1 that when the bias point is at mV_{π} ($m=0, \pm 1, \pm 2, \dots$), we can obtain the best carrier to second-order harmonic distortion ratio, as expected. From Fig.2, we can see that when the bias voltage is offset slightly from the inflection point, the second-order NLDs increase sharply, while the third-order NLDs decrease slowly. For example, for a bias offset of $0.1V_{\pi}$, the $\omega_1+\omega_2$ components increase from non-existent to about -30 dBc, and both the fundamental carrier and the $\omega_1+2\omega_2$ component decrease by 0.44 dB (i.e., C/CTB remains constant). The small change of fundamental carrier power indicates that the change of OMI depends critically on the final bias point, i.e., OMI can be increased or decreased, depending on if the DC offset gives lower or higher optical power. On the right axis of Fig.2, we also see that when the offset is positive, the DC power can be increased (up to 3 dB). For example, for a $0.1V_{\pi}$ offset, the DC power increases by about 1.15 dB.

To summarize our analysis so far: when the bias voltage is offset from the inflection point, the resultant CSOs can be increased significantly, and they can be used to compensate the CSOs generated from the transmission system. In the mean time, the changes of the resultant CTB is small, while CNR and DC power can vary depending on the offset direction.

Although we have proved that significant CSOs can be generated from the optical transmitter by offsetting the bias from inflection point, we cannot be sure about whether the phase of these CSOs are in or out of phase with respect to the transmission system-generated CSOs. Fortunately, we note that we can change the sign of the CSOs by changing the direction of bias offset. For instance, the CSOs due to $+0.1$ and $-0.1V_{\pi}$ offsets are 180° out of phase with respect to each other.

III. EXPERIMENTAL RESULTS

Seventy-seven random-phased continuous-wave (CW) carriers with 6 MHz spacing (starting from 55.25 MHz), from a matrix generator were used to modulate a $1.3 \mu\text{m}$ LiNbO₃ balanced bridge interferometer (BBI) CATV modulator, which has dual outputs. By using a $1.3 \mu\text{m}$ distributed-feedback (DFB) laser, both optical outputs of the modulator reached 3.5 dBm. The optical modulation index per channel (OMI/ch) is about 3% . The BBI modulator had a bias control circuit to control and to stabilize the modulator's bias point. It should be noted that the conventional Schottky diode-based pre-distortion circuit [1] was not used. Between the external modulator and the optical receiver are two adjustable optical attenuators, a commercial available multiple-quantum-well (MQW) SOA, and two optical isolators before and after the MQW-SOA to minimize the multiple reflection effect. The MQW-SOA had a low polarization sensitivity (~ 0.5 dB) and a low gain ripple performance (< 0.3 dB). At a bias current of 300 mA, the MQW-SOA had a fiber-to-fiber gain of 28.9 dB with a gain peak at 1310 nm. When the SOA input power level was at -14.3 dBm and the modulator was bias at the inflection point, the received RF spectra at three different frequency bands are shown in Fig.3(a). The three frequency bands include those channels at low-frequency range (50 -

100 MHz), middle-frequency range (290-330 MHz), and high-frequency range (520-560 MHz). We can see that the worst case C/CSO in the three frequency bands were 18, 24, and 23 dB, respectively. After the modulator bias point was offset by $0.24 V_{\pi}$, the worst case C/CSO in all three frequency bands were significantly improved to 34, 40, and 32 dB, respectively, as can be observed in Fig.3(b). These results can indeed demonstrate the feasibility of our proposed linearization technique.

IV. DISCUSSIONS

Comparing the CNR before and after the bias offset of $0.24 V_{\pi}$, we can see in Figs.3(a) and 3(b) that the CNR was improved by about 4 dB in the latter case. This is because when the optical power was lowered, the OMI/ch was increased and the shot noise level was decreased, and both contribute to increase the resultant CNR.

Another point worth emphasizing is that, for a BBI modulator with dual outputs, when we change the bias point to cancel the CSOs generated in the transmission system, only one of the dual outputs can work effectively. This is because the CSOs generated from the two BBI outputs are 180° out of phase. This phenomenon implies that this technique is best applied to an MZI with a single output.

V. CONCLUSION

We have demonstrated, both analytically and experimentally, that by offsetting the bias point of a MZI modulator from its inflection point, one can obtain sufficient CSOs from the MZI-based transmitter to compensate those CSOs generated from an in-line SOA. The SOA carrier-modulation-induced CSOs were suppressed by as much as 9 to 16 dB over the entire CATV band (from 50 to 550 MHz). We believe that the same technique can also be applied to electro-absorption modulators.

VI. REFERENCES

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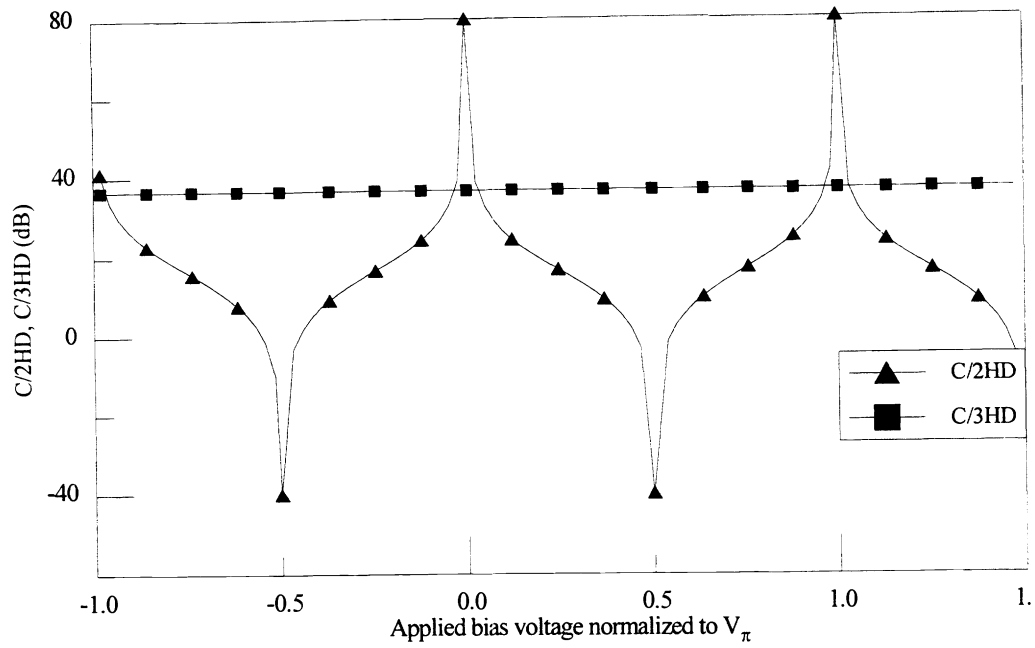


Fig. 1 C/2HD, C/3HD versus applied bias voltage when the MZI modulator is modulated by a single tone with an OMI = 0.6.

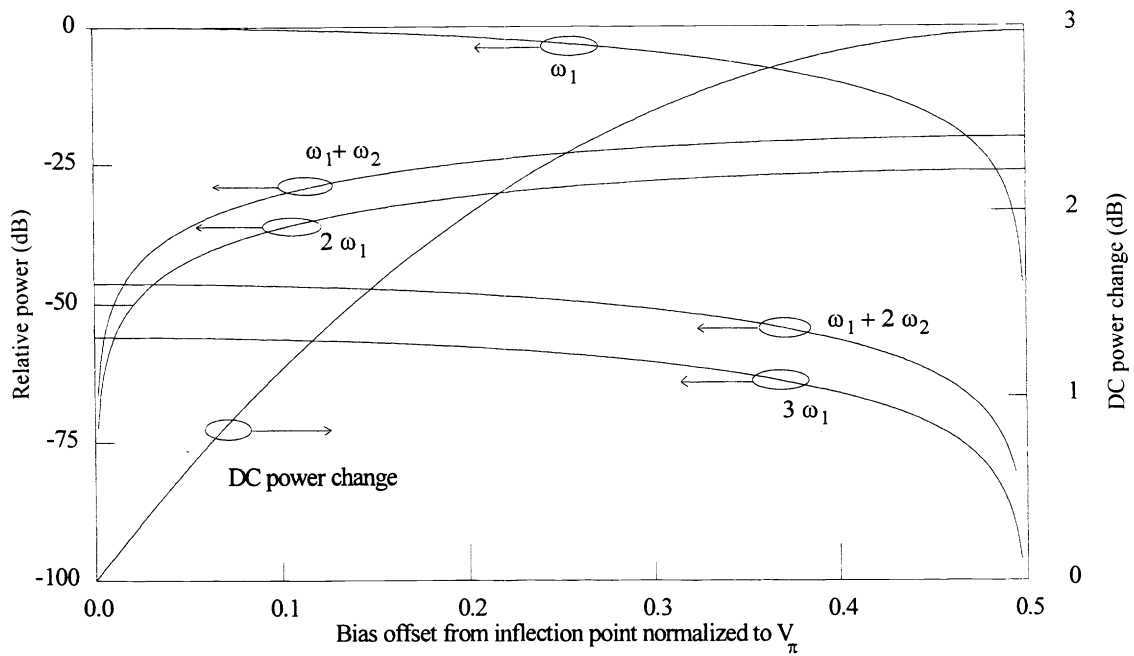
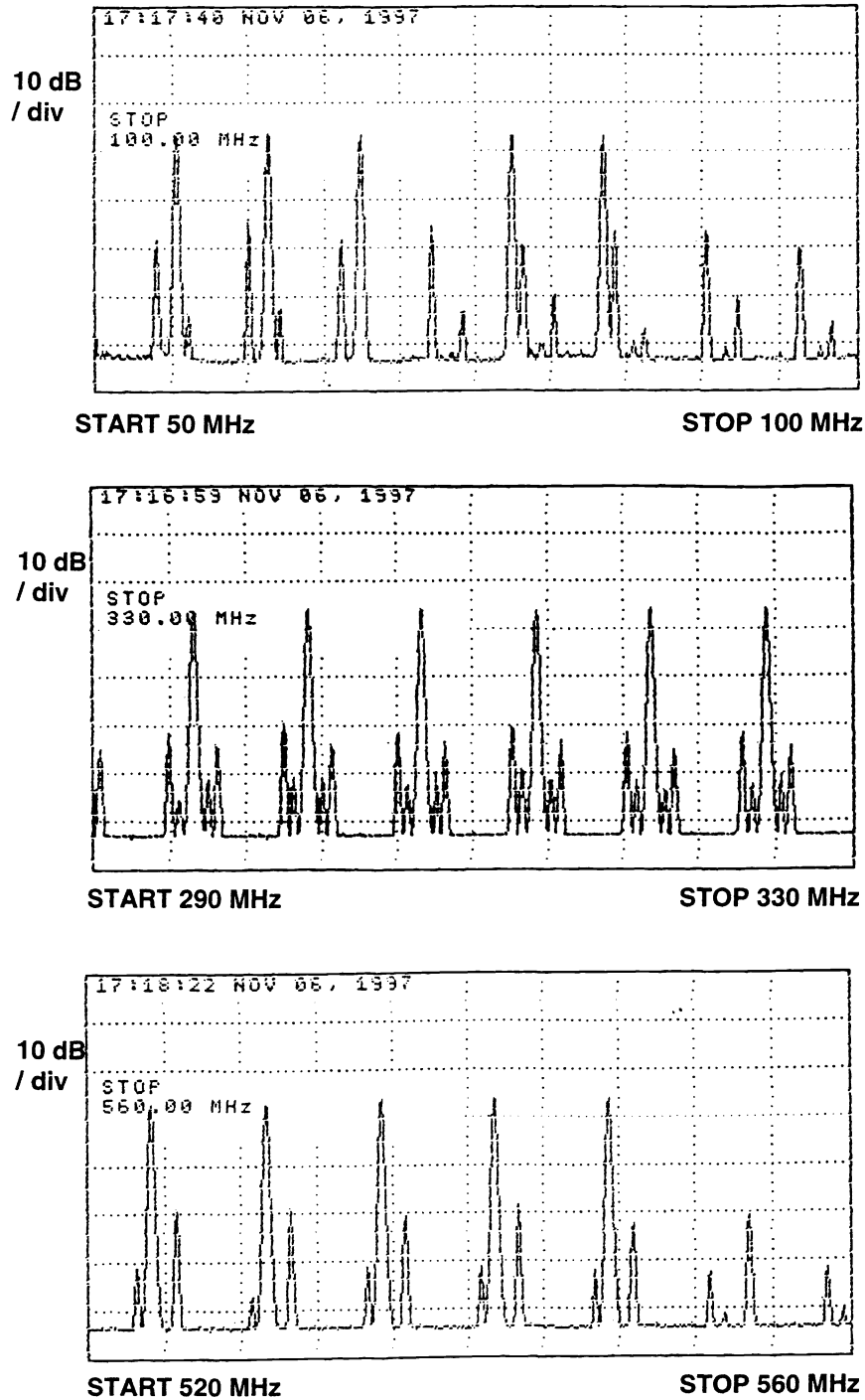
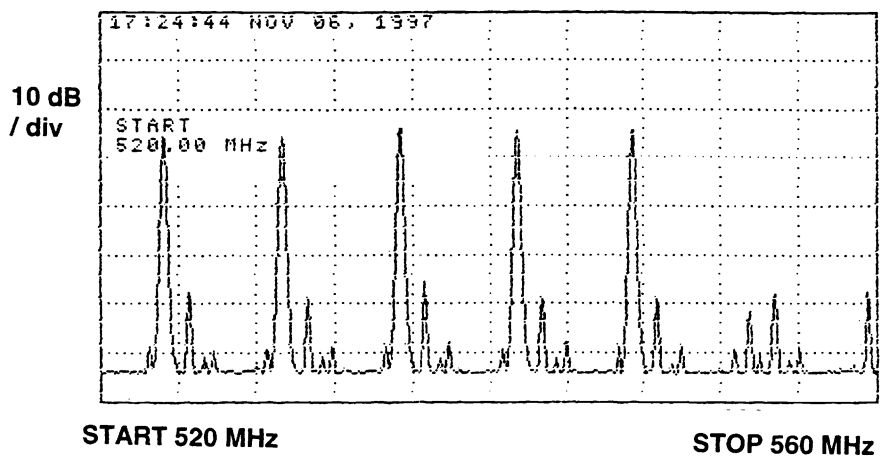
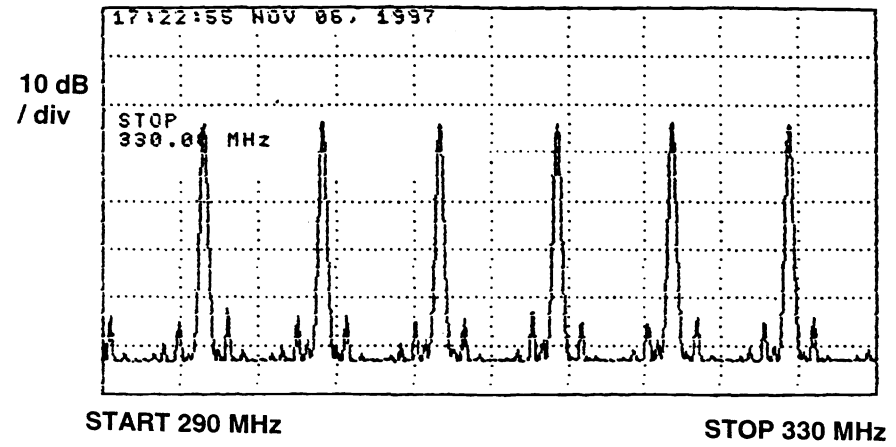
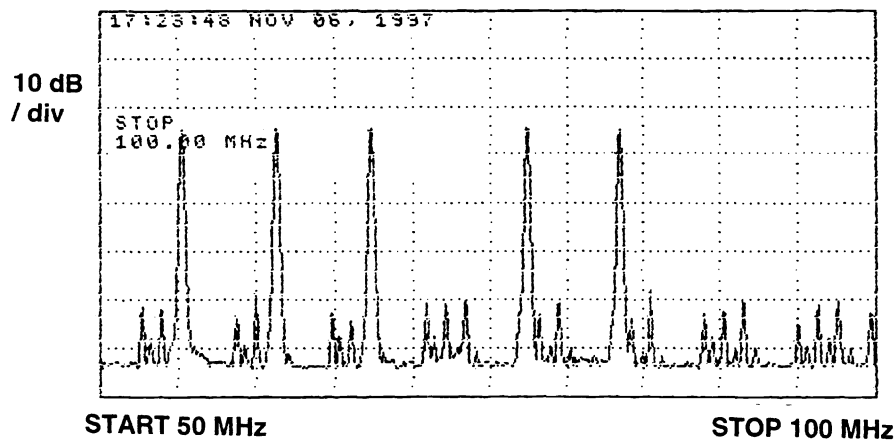


Fig. 2 Relative power and DC power change versus the bias offset from inflection point. The MZI modulator is modulated by two tones (OMI/tone = 0.2).



(a)

Fig. 3 The received RF spectra of an externally-modulated system with an in-line MQW-SOA when the MZI modulator is biased at (a) inflection point and (b) $0.24 V_{\pi}$ offset from the inflection point, respectively. (top: 50-100 MHz, middle: 290-330 MHz, bottom: 520-560 MHz) (resolution bandwidth = 100 kHz)



(b)