INTERFACES FOR HIGH-SPEED FIBEROPTIC LINKS

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ABSTRACT

An analysis of directly and externally modulated fiberoptic links is presented here. The theoretical analysis is based on the signal flow graph of the interface circuits to laser diode, Mach-Zehnder electro-optic modulator, and pin photodiode. The system parameters, such as gain, noise figure, two-tone intermodulation distortion, and dynamic range, are expressed as a function of frequency. Furthermore, fiberoptic link analytical models are compared with the experimental results obtained on custom designed directly modulated FO link at 12GHz and externally modulated FO link at 900MHz.

INTRODUCTION

High-speed fiberoptic (FO) links seem destined for a major role in many microwave circuits and systems [1]. Applications include antenna remoting and distribution networks, delay lines, and optical control functions of microwave devices. Although for different system configurations the specifications in terms of the operating frequencies, bandwidth, noise and dynamic range requirements are different, common to all these systems is the use of FOlinks; thus, an accurate modelling of the FO link performance will aid the system designer in comparison of the viable architectures. Most FOlinks designed for microwave applications are of a relatively short-to-medium length (up to 1 km), and intensity detection techniques are commonly used. The intensity modulation technique of light is either direct modulation of a semiconductor laser diode or electro-optic external modulation of laser light using a Mach-Zehnder modulator. A simplified system block diagram of directly and externally FOlink distribution networks is shown conceptually in Fig. 1.

Until now, a full analytical model that presents the important link parameters for directly and externally modulated links—such as gain, noise figure, two-tone intermodulation distortion, dynamic range—had not been developed, at least in a mode readily intelligible to the microwave engineer. Although some attempt has been made to explain the link performance in terms of equivalent circuit parameters [3-6], these models suffer from inaccurate performance prediction for broadband FO link performance. Goal of this tutorial paper is to present the full derivation of the directly and externally modulated FO link parameters and to verify the analytical models experimentally.

DIRECTLY MODULATED FO LINKS

Gain Analysis

The gain of a fiber-optic link can be calculated in terms of microwave scattering parameters through the signal flow graph (SFG) technique. The transducer gains of the optical transmitter and optical receiver are derived separately and then combined to yield the gain of the complete link. When a directly modulated semiconductor laser diode is employed in the optical transmitter, the SFG is obtained by considering the forward-bias junction resistance of the laser diode to be load termination of a two-port network consisting of the microwave impedance-matching circuit and the other device parameters. The schematic diagram and SFG for the transmitter in a direct modulation link are shown in Fig.1a. Here the output power of a fiber-optic link depends on the amplitude of photocurrent, I_{det}, generated in the detector, which is, in turn, proportional to the rf current, I_{rf}, through the laser diode's active region. The transducer gain of the directly modulated laser-based optical transmitter module is calculated as [7]:

$$G_{Tx} = \frac{P_{out,\,Tx}}{|b_{sL}|^2} = \frac{|S_{21L}|^2 \times \left(1 - |\Gamma_{las}|^2\right)}{\left|1 - S_{22L}\Gamma_{Las}\right|^2} .$$

The link current transfer function, H_L, is defined as the ratio of detector current to rf current across the laser. Assuming operation at frequencies below the 3dB bandwidth of the laser and pin photodiode, the input power to the optical receiver is therefore related to the optical static parameters:

$$|H_L|^2 = (\eta_L K_L L K_D \eta_D)^2$$

where η_L is the laser diode external quantum efficiency, η_D is the detector responsivity, L is the optical attenuation in the fiber, and K_L, K_D are the laser-to-fiber and fiber-to-detector coupling efficiencies, respectively.

The schematic diagram and SFG for the optical receiver is also shown in Fig.1a.When a reverse-biased pin photodiode is employed in the optical receiver, the detected photocurrent and the junction resistance are the source and source resistance exciting a two-port network, which consists of the device parasitics and a matching circuit. As in the case of the transmitter, the output microwave power is derived as [7]:

$$G_{Rx} = \frac{P_{out}}{|b_{sD}|^2} = \frac{|S_{21D}|^2}{\left|1 - S_{11D}\Gamma_D\right|^2} . \quad (1)$$

The transducer gain of the direct modulation link is thus obtained from the optical transmitter and receiver gains and the square of the link current transfer function; i.e.,

$$G = \frac{P_{out,Tx}}{P_{av,\,Rx}} = G_{Tx} \times |H_L|^2 \times G_{Rx}$$

$$= \frac{|S_{21D}|^2\ |S_{21L}|^2\,(1 - |\Gamma_{las}|^2)\ (\eta_L K_L L K_D \eta_D)^2}{|1 - \Gamma_{las}\,S_{22L}|^2\ |1 - \Gamma_{SD}\,S_{11D}|^2} . \quad (2)$$

Noise Analysis

In short and medium haul directly modulated FO links, the thermal noise contributions of the transmitter and receiver are

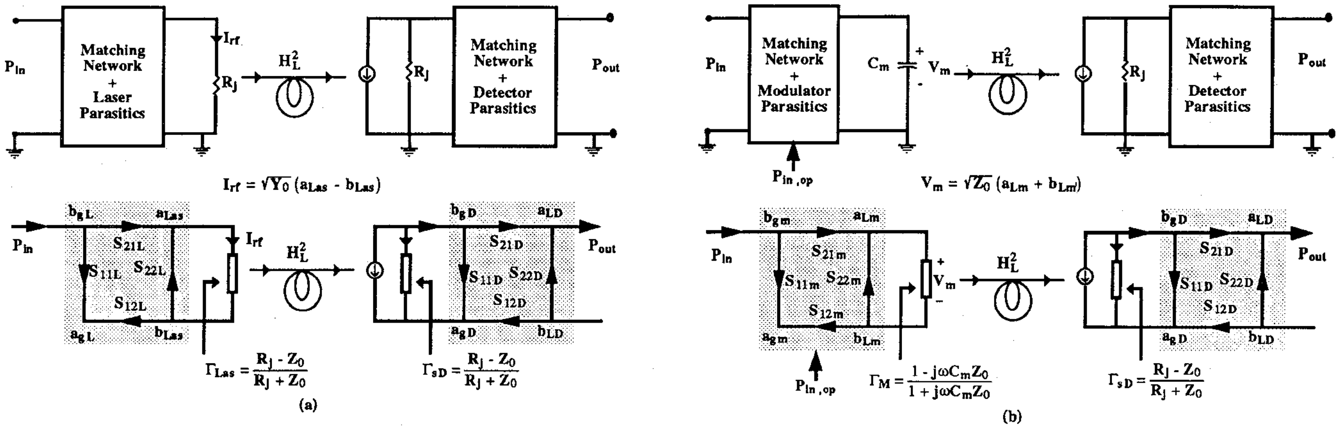

Fig. 1 Conceptual drawing of intensity detected fiberoptic distribution network; a) directly modulated, b) externally modulated.

insignificant as compared to the laser's RIN or the detector's shot noise. These are given as

$$N_{RIN} = RIN(f)\,(I_b - I_{th})^2\,(\eta_L K_L L K_D \eta_D)^2 \times \frac{|S_{21D}|^2}{|(1-\Gamma_{SD} S_{11D})|^2} B Z_0$$

$$N_{shot} = 2e\left[(I_b - I_{th})(\eta_L K_L L K_D \eta_D) + I_d\right] B \times \frac{|S_{21D}|^2}{|(1-\Gamma_{SD} S_{11D})|^2} Z_0$$

The total noise output power is expressed in terms of the link noise figure, NF, as

$$N_{out} = N_{RIN} + N_{shot} = kT \times B \times G \times NF,$$

where kT•B is the thermal noise power at the input of the link.

Intermodulation Distortion Analysis

The distortion charactersitics in a direct modulation link are analyzed with respect to the modulation index m of the laser which is given as:

$$m = \frac{I_{rf}}{I_b - I_{th}}$$

We define the term IMD/C as the ratio between the optical third order intermodulation product and the fundamental of the optical signal. The total optical power out of the laser is given in [8]. From that expression, we obtain the optical power out of the laser at the fundamental and the intermodulation frequency as:

$$P_{\omega_1} = \frac{2 P_0 I_1(a_1)}{I_0(a_1)} \mathrm{Cos}(\omega_1 t)$$

$$P_{2\omega_2-\omega_1} = \frac{2 P_0 I_2(a_2) I_1(a_1)}{I_0(a_2) I_0(a_1)} \mathrm{Cos}[(2\omega_2-\omega_1)t]$$

where $I_k(a_i)$ is the modified Bessel function of order k and a_i (i=1, 2) are defined in terms of the optical modulation index [8]. Thus we obtain IMD/C as

$$\frac{IMD}{C} = \frac{P_{2\omega_2-\omega_1}}{P_{\omega_1}} = \frac{I_2(a_2)}{I_0(a_1)}$$

Small signal expansion of the modified Bessel function results

$$\frac{IMD}{C} \approx \frac{a_2^2}{8}$$

At the third order intercept IMD/C = 1, using the value of a_2 at the intercept we can find the value of modulation index m at the third order intercept, as m_{int}. The input and output powers at the intercept point are calculated using the value of m_{int} as:

$$P_{in,int} = \frac{m_{int}^2 (I_b - I_{th})^2 |1 - S_{22L}\Gamma_{Las}|^2 Z_0}{|S_{21L}|^2 (1 - |\Gamma_{Las}|^2)}$$

$$P_{out,int} = P_{out,int} \times G \qquad (3)$$

The spurious-free dynamic range is defined as

$$SFDR = \left(\frac{P_{out,int}}{N_{out}}\right)^{\frac{2}{3}} \qquad (4)$$

Experimental Results

A direct modulation link was developed at a frequency of 12 GHz with an InGaAsP DFB laser diode manufactured by AT&T. This device emits at the 1.3 µm wavelength and η_L=0.26 mW/mA above laser threshold current of 13 mA. The matching detector was a GTE single-mode fiber-pigtailed pin photodiode with a responsivity of η_D=0.56 mA/mW and a modulation bandwidth of 15 GHz. The laser diode and pin photodiode were reactively matched using distributed-element.

Optical power was coupled from the laser to 8 µm of a single mode fiber and then to the active region of the detector with a link current transfer function of H_L = 0.058. The predicted gain using Eq. 2 is plotted alongside the measured gain in Fig. 2. The plot of the measured rf input versus the rf output power, of the fundamental and the third order intermodulation product for the 12GHz link is shown in Fig. 3. The calculated noise floor level is at -80.1 dB/MHz, matching well with the measured noise levels. The plot also shows the measured dynamic range, which compares well to the calculated spurious-free dynamic range of 57.33 dB•MHz$^{2/3}$ from Eq. 4.

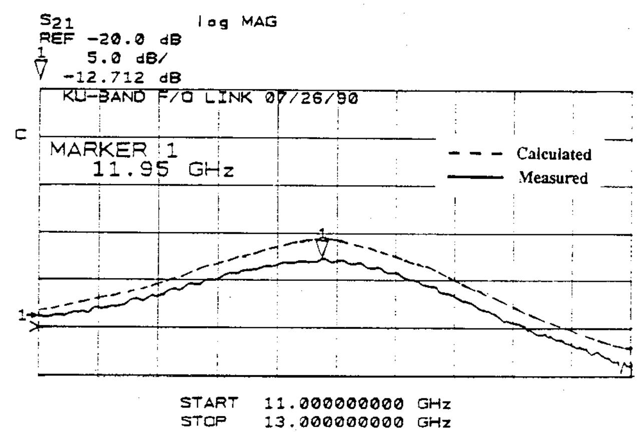

Fig. 2. Insertion loss ($|S_{21}|^2$) comparison of the experimental and analytical results of a directly modulated FO link at 12GHz.

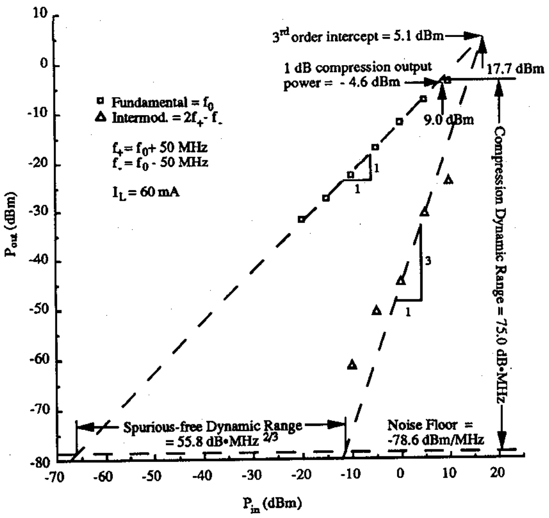

Fig. 3. Dynamic range comparison of the experimental and analytical result of a 12GHz directly modulated FO link.

EXTERNALLY MODULATED FO LINKS

Gain Analysis

The schematic diagram and SFG for the externally modulated FO link is shown in Fig.1b. In a Mach-Zehnder interferometric modulator the microwave signal modulates the optical carrier by impressing voltage V_m, across the capacitance C_m. This voltage is related to the microwave input power through a two-port network, consisting of the microwave impedance-matching circuit and the other device parameters in the equivalent circuit of the modulator, and is expressed as:

$$|V_m| = \sqrt{\frac{Z_0 P_{in,rf} |S_{21m}|^2 |1+\Gamma_M|^2}{|1 - S_{22m}\Gamma_M|^2}}$$

The optical output of the modulator is represented in terms of the d.c. optical input to the modulator as:

$$P_{out,op} = P_{in,op} \operatorname{Cos}^2\left(\frac{\pi}{4} - \frac{\pi V_M}{2V_\pi}\right)$$
$$= P_{in,op}\left[1 + \operatorname{Sin}\left(\frac{\pi V_M}{2V_\pi}\right)\right]$$

where, $V_M = V_b + V_m \operatorname{Sin}\omega t$
V_π = bias voltage required for 100% modulation

The d.c. bias applied to the modulator electrodes, V_b controls the operating point of the modulator. The modulated output optical power reduces to

$$P_{out,op} = P_{in,op}\left(\frac{\pi V_m}{2V_\pi}\right)\cos\left(\frac{\pi V_b}{V_\pi}\right)$$

At the linear bias point, i.e. halfway between the on and off switching voltages, $V_b = 0$ and the output optical power is even more simplified. The external modulators output optical power is detected by the optical receiver and converted to photocurrent. The photocurrent is transformed through the receiver with the receiver gain as was shown in Eq. 1. Therefore, the small-signal gain of the external modulation link operated at its linear dc bias voltage is obtained as:

$$G = \left(\frac{\pi \eta_L \eta_{op} P_{in,op} Z_0}{2 V_\pi}\right)^2 \times \frac{|S_{21M}|^2 |S_{21D}|^2 |1+\Gamma_M|^2}{|1 - \Gamma_M S_{22M}|^2 |1 - \Gamma_{SD} S_{11D}|^2} \quad (5)$$

where $\eta_{op} = L \bullet K_D$.

Noise Analysis

As in the directly modulated case, the thermal noise of the optical transmitter and receiver modules in the externally modulated fiber optic links are insignificant. The dominant noise contributions to the noise output power are the shot noise of the detector and the excess noise of the laser, and are expressed as:

$$N_{shot} = 2e\left[\left(\frac{\eta_{op}\eta_D P_{in,op}}{2}\right) + I_d\right] B \frac{|S_{21D}|^2}{|1 - \Gamma_{SD} S_{11D}|^2} Z_0$$

$$N_{excess} = \left[RIN\left(\frac{\eta_{op}\eta_D P_{in,op}}{2}\right) - 2e\right] \times \left(\frac{\eta_{op}\eta_D P_{in,op}}{2}\right) B \frac{|S_{21D}|^2}{|1 - \Gamma_{SD} S_{11D}|^2} Z_0$$

where I_d corresponds to the pin photodiode's dark current. As in the direct modulation case, the output noise power is related to the input noise power, $kT \bullet B$, and the link noise figure, NF.

Intermodulation Distortion Analysis

The distortion characteristics of the external modulation link are analyzed with respect to the modulation index m, which for a Mach-Zehnder modulator at the linear dc bias point (V_b=0) is defined as:

$$m = \frac{2 V_m}{V_\pi}.$$

In terms of the optical third-order intermodulation product, the IMD/C ratio obtained from the small-signal transfer function is found from the carrier and intermodulation optical powers as a function of the modulation voltage. From the expression for optical power out of the modulator that at V_b=0,

$$P_{out,op} = \frac{P_{in,op}}{2}\left[1 + \sin\left(\frac{\pi V_m}{V_\pi}\sin\omega t\right)\right].$$

This result can be expressed in terms of the Fourier expansions, with the coefficients expressed in terms of Bessel functions. Therefore, the optical power out of the modulator at the fundamental and intermodulation frequencies are

$$P_{\omega_1} = P_0 J_0(a) J_1(a) \sin\omega_1 t$$

$$P_{2\omega_2-\omega_1} = P_0 J_1(a) J_2(a) \sin(2\omega_2 - \omega_1)t$$

where $J_k(a)$ denotes the ordinary Bessel function of order k and $a = (\pi V_m/V_\pi)$. Thus,

$$\frac{IMD}{C} = \frac{P_{2\omega_2-\omega_1}}{P_{\omega_1}} = \frac{J_2(a)}{J_0(a)},$$

Using the small signal Bessel function expansion results in:

$$\frac{IMD}{C} \approx \frac{a^2}{8}$$

and the third-order intercept point occurs at a modulation index of $m = \sqrt{32}/\pi$. Thus, the rf input power to the link at the third-order intercept is:

$$P_{in,int} = \frac{8 V_\pi^2 |1 - S_{22m}\Gamma_M|^2}{\pi^2 Z_0 |S_{21m}|^2 |1+\Gamma_M|^2}$$

and

$$P_{out,int} = P_{in,int} \times G \quad (6)$$

As for the direct modulation link,

$$SFDR = \left(\frac{P_{out,int}}{N_{out}}\right)^{\frac{2}{3}} \quad (7)$$

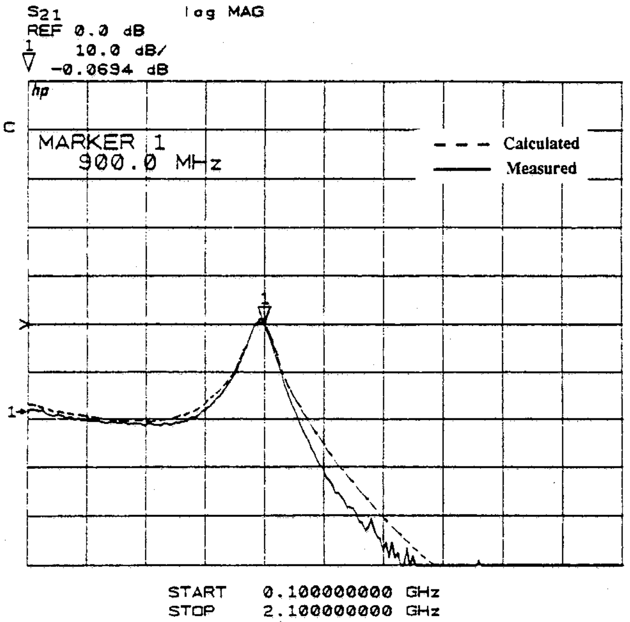

Fig. 4. Insertion loss ($|S_{21}|^2$) comparison of the experimental and analytical results of an externally modulated FO link.

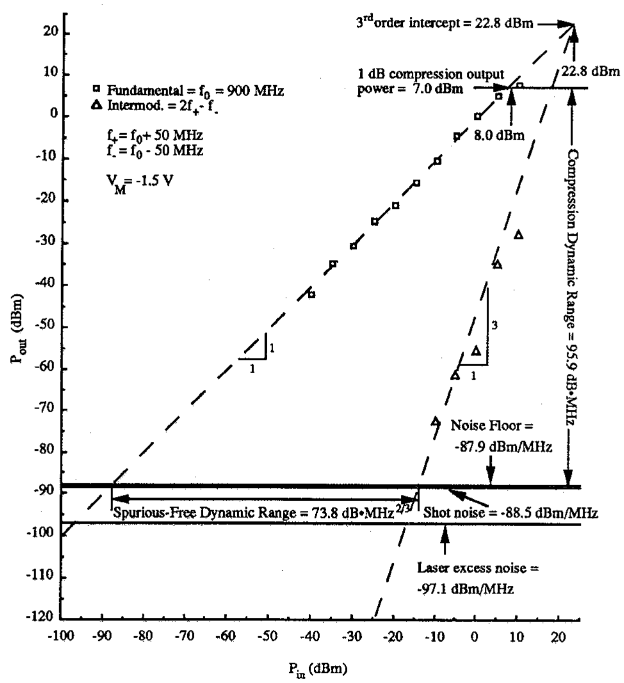

Fig. 5. Dynamic range comparison of the experimental and analytical results of an external modulated FO link at 900 MHz. The third order intercept point and noise floor level are also rendered.

<u>Experimental Results</u>

For the experimental external modulation link a Crystal Technology 1.3 µm $LiNbO_3$ Mach-Zehnder modulator was selected with a switching voltage $V_\pi = 8.3$ V, and a modulation bandwidth of 3 GHz, and 4.2 dB fiber-to-fiber optical insertion loss. A British Telecom & DuPont (BT&D) InGaAs pin photodiode with a responsivity of $\eta_D = 1.0$ mA/mW was employed in the detector module. Using the deembedded S-parameters of devices, the reactively impedance matching network were developed at 900 MHz.

To maximize the gain and dynamic range of the external modulation link, high power single-mode fiber-pigtailed Nd:YAG laser source manufactured by AMOCO was employed as source. The solid-state laser and impedance-matched detector module were optically coupled to the modulator's input and output fibers, respectively. The modulator was biased at $V_M = -1.5$V, a dc photo-current of $I_{DC} = 4.3$ mA was measured.

Measured gain of the link is plotted as a function of frequency in Fig. 4 and compared with calculated results using Eq. 5. At 900 MHz, a noise figure of 24.1 dB was predicted, comparable to the measured noise figure of 24.3 dB at this frequency. Shown in Fig. 5 are the results of a two-tone intermodulation distortion measurement as well as a measurement of the output noise floor of the external modulation fiber-optic link. The 22.8 dBm measured third-order intercept output power and resultant SFDR of 73.8 dB•MHz$^{2/3}$ closely match the 21.1 dBm and 73.6 dB•MHz$^{2/3}$ values predicted by Eqs. 6 and 7, respectively.

CONCLUSIONS

Analysis of the experimental results of directly and externally modulated high-speed FO links are persented terms of gain, noise figure, and dynamic range. The analytical expressions are derived through SFG, which accurately predict experimental results.

ACKNOWLEDGEMENTS

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