Tutorial on Microwave Photonics Modulation and Link Performance

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Abstract -- Microwave photonics is the practice of using optical carriers to generate, process, or distribute signals in the microwave spectrum. In this paper, techniques for the optical distribution of microwave signals are described. In general, these systems employ microwave links which involve: 1) the modulation and demodulation of microwave information with respect to an optical carrier, 2) the propagation of the modulated signal on fiber optic cables, and 3) the limitations to the fidelity of the signal, which are due to both linear and nonlinear processes.

***Index Terms — photonics, microwave photonic link, radio over fiber, fiber optic cable, photodiode, optical modulation,* Mach-Zehnder modulator, direct laser modulation.**

I. Introduction

Fiber optic cable is an optical waveguide that exhibits very low loss, EMI immunity, and very small size and mass. Additionally, modern semiconductor lasers enable the modulation of very large bandwidth microwave signals onto an optical (laser) carrier. Consequently, microwave photonics is effective for the distribution of microwave signals for applications that benefit from some or all of these attributes. These include antenna remoting, radar and signal processing, broadband signal collection, LO distribution, and phased array beam steering, among others. The development of a microwave photonic link requires an effective means of modulation and demodulation, and an understanding of the limitations caused by linear and nonlinear effects of the modulation, demodulation, and transmission media. This paper provides a tutorial on these topics, with emphasis on intensity modulation (IMOD), the simplest and most common link structure.

II. Intensity Modulation

A microwave photonic link consists of an RF input and output, separated by an optical source, a modulator (which in some cases is the same component as the source), a transmission medium (fiber optic cable), and a demodulator. The RF input and output are typically referenced to 50 ohms.

A complex information signal $\vec{m}(t)$ has complex envelope $\vec{a}(t)$ given by

$$\vec{a}(t) = 1 + \vec{m}(t) \qquad (1)$$

Since the optical carrier frequency ω_c is on the order of 10^5 GHz and the information signal m(t) is on the order of 10^2 GHz or less, the complex electric field of the modulated optical signal is slowly varying (with respect to the optical carrier) and can be approximated as

$$\vec{e}(t) = \vec{a}(t)e^{j\omega_c t} \qquad (2)$$

This in turn leads to a slowly varying intensity or power:

$$p(t) = \vec{e}(t)\vec{e}^*(t) = \tfrac{1}{2}\left|\vec{a}(t)\right|^2$$

$$= \tfrac{1}{2}\left[1 + \left|\vec{m}(t)\right|^2 + 2\,\mathrm{Re}\{\vec{m}(t)\}\right] \qquad (3)$$

If the modulation is small signal, $|m(t)| << 1$ and the middle term of (3) can be ignored. Then

$$p(t) \propto 1 + 2\,\mathrm{Re}\{\vec{m}(t)\} \qquad (4)$$

Thus a *real* RF field modulates the *intensity* of the optical carrier. Note the square-law relation, wherein a voltage or current directly induces a change in intensity.

III. Direct Detection

Detection of the microwave modulation can be accomplished using a semiconductor photodiode operating in the photovoltaic region, whereby photons recombine within a diffusion region to generate electrons (current). For a P-I-N diode, the best case is one e^- for each photon, referred to as the quantum limit. Avalanche photodiodes generate >1 photon per e^-, resulting in recombination gain. In either case the ensemble average of current with respect to optical power is called the responsivity.

$$R = \eta q / \hbar\omega \quad \text{(A/W)} \qquad (5)$$

Where η is the detector quantum efficiency, q is the electron charge, and ħω is the photon energy. The microwave current resulting from the optical power envelope is, from (4):

$$i(t) \propto R\left[1 + 2\,\mathrm{Re}\{\vec{m}(t)\}\right] \qquad (6)$$

Eq. 6 shows that a link consisting of an intensity-modulated optical carrier followed by a directly-detected receiver is *linear*. The amplitude and phase of the microwave signal are (ideally) preserved, and the complex microwave output spectrum is the Fourier transform of the input microwave signal:

$$\vec{M}(\omega) \propto F\{\vec{m}(t)\} \tag{7}$$

The slowly varying approximation used in (3) requires averaging of optical carrier power over several optical cycles. [1] Thus, optical carrier phase information is lost. The optical intensity spectrum of an IMOD signal is analogous to an amplitude modulated (AM) RF voltage: a carrier with upper and lower sidebands. One benefit of IMOD is that little or no microwave phase noise is induced, making IMOD links attractive for distribution of high-fidelity time and frequency signals.

IV. Other Modulation Formats

If m(t) is imaginary then optical phase is modulated, rather than intensity. For a purely imaginary m(t) the optical signal has constant envelope. This architecture generally requires increased complexity in the demodulation, primarily due to difficulty in efficient and stable phase detection at THz frequencies.

Coherent detection can be accomplished by combining the detected complex-modulated envelope with a reference optical LO. This technique preserves both optical amplitude and phase, but requires additional filtering and higher laser stability.

Up- and down-converting optical links can be built using multiple modulation stages. For example, cascaded modulation with 2 microwave signals results in sum and difference products from:

$$p(t) \propto 1 + 2\,\mathrm{Re}\{\vec{m}_1(t)\vec{m}_2(t)\}. \tag{8}$$

A plethora of microwave modulation architectures are thus possible using optical carrier modulation techniques. Combined with microwave photonic generation and processing [2], complicated microwave systems can be developed.

V. Methods of Intensity Modulation

Two primary methods are used to practically perform IMOD: direct and external. When directly modulating, the microwave signal is applied directly to the bias of a semiconductor laser diode, as shown in Figure 1. The resulting optical power is given by:

$$p(t) = \eta_L[(I_L - I_{th}) + i_m(t)] \tag{9}$$

where I_L is the laser DC bias, I_{th} is the laser threshold current, and $i_m(t)$ is the microwave current; illustrated in Figure 2.

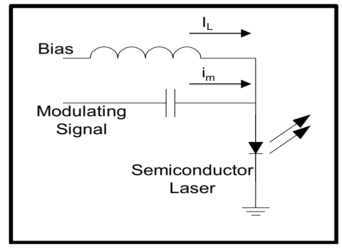

Fig. 1. Direct modulation: microwave current $i_m(t)$ is coupled directly into a laser diode, along with the bias current I_L.

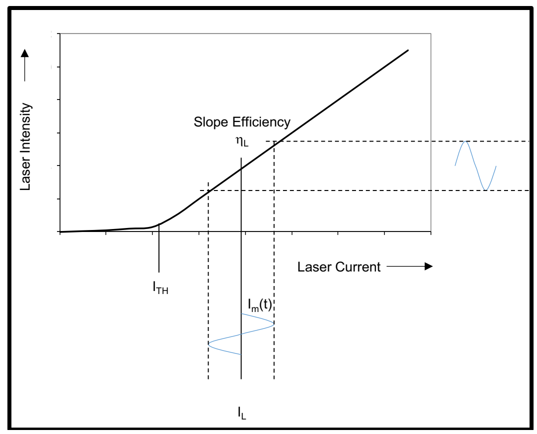

Fig. 2. Intensity directly modulated by microwave current.

External modulation makes use of a material property of a secondary device in order to change the intensity of an optical signal propagating through it. A common approach is to exploit the electro-optic (EO) effect, which is a field-dependent characteristic of certain crystals such as lithium niobate ($LiNbO_3$). The most common implementation of the EO effect is the Mach-Zehnder modulator (MZM), shown in Figure 3. An optical waveguide is diffused into the surface of the material, and an input optical signal is split among two paths. A microwave signal is applied orthogonally across the RF electrodes in one path. The index of refraction in the optical direction of propagation changes in proportion to the RF electric field strength (the EO effect), which changes the phase of the optical field in that path. When the two paths are summed at the output, the resulting optical intensity can take on any value between zero and maximum:

$$p(t) \propto \cos^2\left(\frac{\pi v_m(t) + \phi}{2V_\pi}\right) \tag{10}$$

Where v_m is the microwave modulating field voltage, V_π is the half-wave voltage of the device (distance between min and max output power), and ϕ is the offset from zero-bias. This follows a raised-cosine relationship as shown in Figure 4. If the bias is set to the midpoint between min and max then small-signal modulation is approximately linear. This bias condition is referred to as quadrature modulation.

Since MZM devices are field-dependent with very little parasitic capacitance, they are capable of operation at very high frequency; over 100 GHz has been demonstrated [3-5].

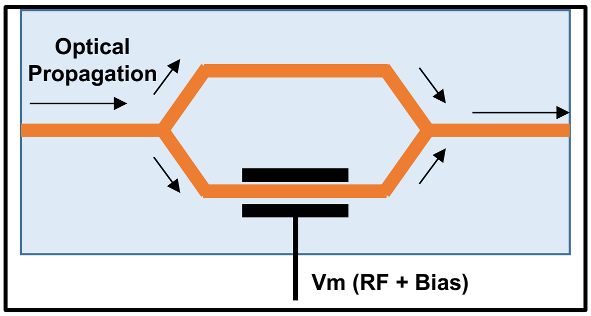

Fig. 3. A Mach-Zehnder modulator showing a diffused optical waveguide on LiNbO3 substrate. The group delay in the lower leg increases in proportion to an applied microwave field.

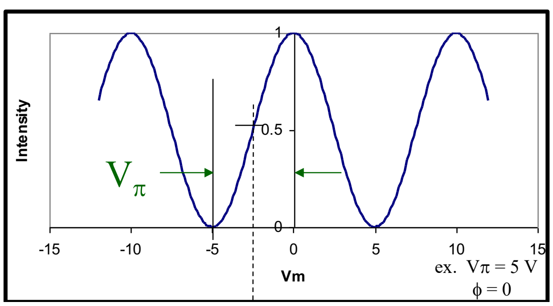

Fig. 4. The raised cosine intensity characteristic as a function of applied field. Linear small signal modulation is possible when the modulator is biased at $V_\pi/2$.

V. Fiber Optic Waveguide

Fiber cable is a cylindrical waveguide consisting of a core whose dielectric constant is greater than a surrounding cladding, both regions are typically made from doped silica glass. The primary solution to the field equations for a step-index, single-mode fiber result in a standing transverse (radial) field confined by the boundary conditions of the clad/core, and a dispersive propagating wave along the cylinder axis (z-directed); the so-called hybrid EM mode (HE_{11}) [6,7].

Because of transverse confinement a propagating field, once properly launched into the core, will not exit through the cladding. Attenuation is due only to absorption in the glass, and is very low. Typical optical attenuation for single-mode fiber is 0.25 dB/km at 1550 nm and 0.5 dB/km at 1310 nm, but will depend on the fiber design.

VI. Performance Limitations

The discussion thus far has focused on the formation of a linear microwave link. This section discusses the limitations to link performance. Qualitatively, a link can be considered to have 3 primary parameters: gain, noise, and nonlinear distortion, as shown in Figure 5.

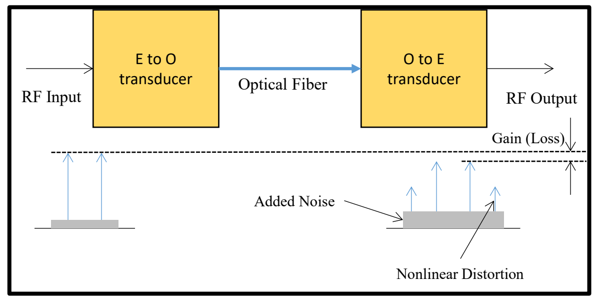

Fig. 5. A microwave link can be characterized by its gain (or loss), its added noise, and its nonlinear distortion.

These parameters can be considered in the context of linear and nonlinear effects. Linear effects can alter the spectral shape of the information signal but cannot introduce new frequencies. Nonlinear effects add new spectral components.

Linear Effects: Microwave Launch

A link to be useable must provide input and output terminals, referenced to a characteristic impedance; e.g. 50 ohm. In the case of direct modulation, for example, a forward biased laser diode has a very small real resistance, often < 5 ohm. This requires a microwave impedance matching network. While a single-frequency match is in general always possible, a microwave link usually needs to provide broadband operation. Due to the limitations inherent in broad-band matching [8,9], a purely reactive network is often impossible. A resistive or lossy matching network is required. Such networks affect the gain and noise characteristics of the link. Similarly, a reverse-biased PIN photodiode presents a very high reactive impedance, and lossy matching is required for broadband operation.

Linear Effects: Noise

The added noise of a fiber link arises principally from 3 sources: 1) laser relative intensity noise, 2) detector shot noise, and 3) thermal noise. A laser generates an optical carrier by exciting electrons to a defined energy value and then stimulating their precipitation to a lower energy level, resulting in a defined energy transition. If all of the electrons follow the same transition, then all of the generated photons will have the same energy (wavelength). The result is a perfectly correlated delta function. In practice, thermal and other considerations cause transitions to undesired states, yielding photons that are not at the same frequency or phase. This appears as optical noise, called Relative Intensity Noise (RIN). This noise is transferred to the photoreceiver, demodulated, and delivered to the microwave load as noise power. RIN noise is not white; it has uneven microwave amplitude. However, it can be treated as white noise in a reasonable narrow band around the carrier.

"RIN" is a laser dependent parameter and described statistically as a spectral ratio of undesired power to average power, expressed in units of 1/Hz, or dB/Hz [10]. Its amplitude is in reference to only the amplitude of the optical carrier. At the detected output, the microwave noise has a fixed relationship to optical power. The average optical power incident on the photoreceiver generates a RIN-noise photocurrent that is delivered to the load as a noise power density. Using the white-noise approximation,

$$N_{rin} = I^2 RINz_0 \qquad (11)$$

Where N_{rin} is the power density (W/Hz), I is the average photocurrent, and z_0 is the characteristic load impedance. The noise power follows the square of the photocurrent, so that a 1 dB increase in optical power (photocurrent) will result in a 2 dB increase in RIN noise.

A random photon arriving at the photoreceiver causes an e^- - hole recombination, resulting in a packet or *shot* of charge, each appearing as a delta function in the time domain. This leads to an ensemble average (DC current) and a noise power delivered to the load that is spectrally flat (white) and has a spectral density of

$$N_{shot} = 2qIz_0 \qquad (12)$$

where q is the electron charge. Unlike RIN, shot noise is proportional to the photocurrent, so a 1 dB increase in optical power corresponds to a 1 dB increase in detected shot noise.

Thermal or Johnson noise at the output results from the contributions of all the real resistive elements of the link and the forward gain from each, and is constant with regard to photocurrent. Most broadband links are *lossy*, so that all of the thermal contributions generated along the link are attenuated before they reach the load. The only measurable output thermal noise is due to the load itself:

$$N_{th} = kT \qquad (13)$$

where k is Boltzmann's constant and T is the reference temperature in Kelvin. The 3 noise densities defined by (11-13) add independently so that the total noise power in a detection bandwidth B is given by:

$$N = I^2 RINz_0 B + 2qIz_0 B + kTB \qquad (14)$$

The bandwidth of the detected noise is not the bandwidth of the optical link. It is the bandwidth of the frequency-selective component of the link, such as a downstream microwave receiver or downconverter. In many cases the link bandwidth capability will exceed the instantaneous processing capability of the microwave system. For this reason the noise of a fiber optic link is often referenced to a bandwidth of 1 Hz.

The noise of the link has 3 distinct regions: RIN, shot, and thermal, as shown in Figure 6 [11].

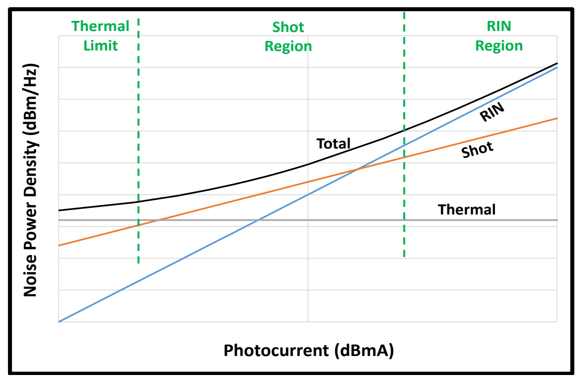

Fig. 6. Noise power at the output of a microwave link is dependent upon the detected photocurrent. 3 regions of operation result: thermal, shot, and RIN.

At low optical power the noise is constant (thermal limit). At moderate power the noise varies 1:1 (in dB) with the power (shot region). At high power the noise increases 2:1 with power (RIN region). In all cases, the signal power delivered to the load follows the detector square-law and varies 2:1 with optical power. The resulting noise figure is therefore minimum and constant in the RIN-limited region, which is the preferred operating point. This is shown graphically in Figure 7.

Linear Effects: Fiber Medium

The fiber cable, in addition to the dissipative loss described above, also exhibits chromatic and polarization-mode dispersion. The more important impact for a microwave link is chromatic dispersion, which is a wavelength-dependent propagation velocity. Since IMOD resembles AM, the information signal is contained in 2 sidebands around the optical carrier.

Dispersion causes the sidebands to arrive at the receiver with different phase, as shown in Figure 8. At certain combinations of modulation frequency and link length, the upper and lower sidebands will arrive out-of-phase, and the detector will provide a null output. This is a linear phenomena affecting the link because it can be compensated using a linear filter (phase equalizer) at the input side. The effects of dispersion need to be understood by the link designer.

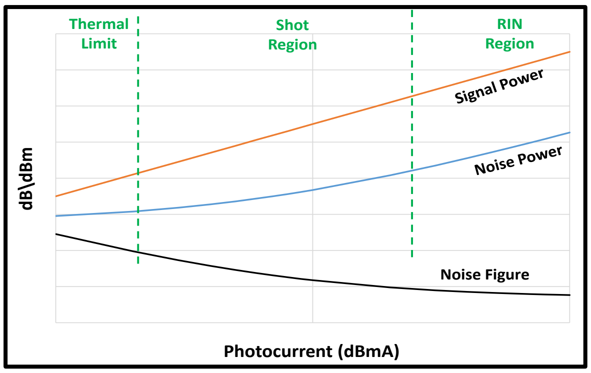

Fig. 7. Both noise and signal increase with the same 2:1 slope in the RIN region, resulting in a minimum and constant noise figure. At very low optical power (thermal limit) the noise figure decreases 2 dB per dB decrease in optical power.

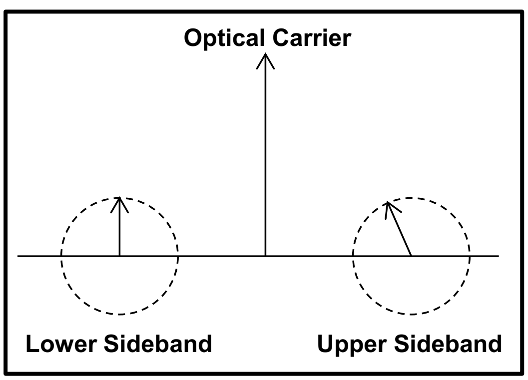

Fig. 8. Chromatic dispersion is the wavelength-dependent propagation velocity in fiber cable.

Nonlinear Effects: Modulator Transfer Function

The modulating device causes nonlinear distortion. In the case of directly-modulated links, gain compression results from large signal operation once the modulation current is large enough to approach threshold (Figure 2). This distortion can have both even and odd order products. Additionally, phase distortion (AM-to-PM conversion) can occur due to *laser chirp* because the laser wavelength is a function of drive level and temperature.

In an EO modulated link the transfer function is a raised cosine (Figure 4), so odd order distortion dominates. Even order distortion tends to be small because the modulation is *balanced* around the quadrature bias point. EO modulation tends to have little or no phase distortion because the carrier is fixed.

Nonlinear Effects: Fiber Medium

The propagation medium, in addition to the linear effects described above, also contributes nonlinear distortion. These effects are highlighted briefly here. Detailed technical treatment can be found in [12]. A link design should include an analysis of these effects.

Stimulated Brilluoin Scattering (SBS) is the creation of a backward-traveling phonon wave that reduces power and adds nonlinear spectral noise in the signal path. It is caused by high instantaneous energy in the core. Below a threshold power level, which depends upon link length SBS does not occur.

Stimulated Raman Scattering (SRS) is due to inelastic photon scattering and results in wavelength translation and gain reduction.

Self-phase Modulation is analogous to AM-PM conversion of a single signal. Cross-phase Modulation arises when the amplitude of one carrier wavelength affects the phase of another, which is akin to AM-PM transfer from one signal to another. 4-wave Mixing is similar to intermodulation distortion. The latter two effects are associated with multiple optical carriers on a single fiber, a technique commonly used for digital networks called Wavelength Division Multiplexing (WDM). These lead to cross-talk between channels, which can be more detrimental in a microwave link than a digital link because microwave links generally require much higher signal-to-noise ratio or dynamic range for linear operation.

VII. Summary

Linear microwave fiber optic links are capable of ultra-wide bandwidth operation into the microwave and millimeterwave regions. Practical implementation approaches have been described, along with linear and nonlinear effects that limit their performance. In most cases, a distributed fiber optic link can be analyzed in the same fashion as a localized RF amplifier, where gain, noise, and linearity are the three primary factors that determine its suitability and impact in a system.

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