A Low-Loss Downconverting Analog Fiber-Optic Link

G. K. Gopalakrishnan, R. P. Moeller, M. M. Howerton, W. K. Burns, K. J. Williams, and R. D. Esman

Abstract—**An analog fiber-optic link for concurrent detection and downconversion of microwave signals is reported. Optical amplification is employed in conjunction with electrical power combining of photodetectors to demonstrate link losses of 19.6 and 22.9 dB at RF carrier frequencies of 9 and 16 GHz, respectively. Analytic expressions validating the experimental observations are also developed. The link may be employed to detect phase sensitive or phase-modulated microwave signals and shows excellent potential for application in sensor systems involving remoting of an antenna element.**

I. INTRODUCTION

TRANSMISSION of radio frequency (RF) signals over an optical fiber offers the advantages of low-loss and immunity to electromagnetic interference. As a result of recent developments in optical fiber-based analog microwave link technology [1], such links are gaining increasing acceptance. In its simplest form, a fiber-optic link (FOL) is comprised of an optical source (which could be either directly or externally modulated), a length of fiber for transmitting the modulated optical signal, and a photodetector (PD) for converting the received optical signal into an electrical signal. Such a link is known as a direct (both RF and optical) detection link and has previously been studied quite extensively [2], [3]. These links have applications in satellite communications systems [4], subcarrier multiplexed (SCM) systems [5], [6], and optically controlled phased-array antenna systems [7].

The drawback of direct detection FOL's lies in the fact that they typically entail a large conversion loss accompanying the electrical-optical-electrical conversion process. Compensation for this loss could be effected by increasing the output optical power (and thereby the PD current) via optical amplification, but this approach is limited by PD saturation [8]. This limitation is particularly important at high frequencies (> a few GHz), as high-speed PD's are constructed with relatively small active areas to reduce device capacitance. Hence they exhibit a relatively low ($\approx$ a few mW) power saturation threshold, beyond which their performance is significantly nonlinear [8]. Thus, for application in broadband sensor systems where very weak high-frequency signals have to be detected, the suitability of the direct detection approach is inhibited by conversion loss, which cannot be significantly improved by increasing the output optical power.

On the other hand, in a typical receiver system, the detected RF signals are usually downconverted to a lower intermediate frequency (IF) to recover the information at baseband. This process is known as heterodyne detection and is an alternative to direct detection. In the context of FOL's, RF heterodyne detection could be accomplished by employing one of the following two techniques: optical heterodyne detection or electrical heterodyne (down-conversion) detection.

In optical heterodyne detection [9], two optical carriers are tuned to an optical difference frequency of Δf, which serves as the microwave local oscillator (LO); one optical carrier is modulated with an RF signal (f_{RF}) and the other is added and mixed with one of the sidebands of the first carrier in a photodetector. A down-converted IF difference signal of $\Delta f - f_{RF}$ appears at the detector. In this technique the issues to be addressed are optical phase noise, polarization management, and tuning speed. Additionally, the complexity of the technique is compounded by the high-speed PD and phase-locked-loop (PLL) circuitry required to offset lock the two optical carriers.

In contrast to optical heterodyne detection, down-conversion detection may be accomplished by employing an external microwave mixer. Here the received RF signal from the PD is applied to a microwave mixer and heterodyned with a LO pump signal. The IF difference signal is then obtained from the IF port of the mixer. As before, the drawback of this approach is that if the RF signal frequency is sufficiently high, then a high-speed PD is required.

Thus, to obtain better link sensitivity an alternate approach is required. We recently demonstrated [10] that a system containing a pair of external interferometric modulators, cascaded in series, both biased at quadrature, may be employed to concurrently detect and downconvert RF signals. Here we adapt this architecture to demonstrate a downconverting FOL (Fig. 1) for application in sensor systems where the antenna element has to be remoted. Here, since the detected IF is a low frequency ($\approx$ few 100 MHz) signal, this approach eliminates the need for high-speed PD's. Thus low-speed PD's with larger active volumes and power saturation thresholds may be employed in conjunction with optical amplification to obtain better link performance. In the ensuing sections of this paper we demonstrate and analyze a downconverting

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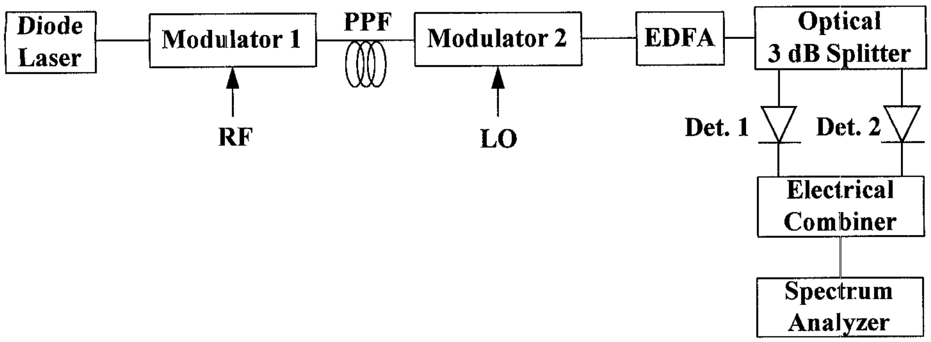


Fig. 1. Block diagram of down-converting fiber-optic link.

FOL employing serially cascaded modulators with optical amplification.

This paper is organized as follows. In Section II we develop analytic expressions to characterize link performance; explicit expressions to evaluate both the conversion loss and the sensitivity of the link are presented. In Section III we discuss in detail the experimental results and employ the analyses of Section II to support the data obtained. Section IV is devoted to discussions, and, finally, the conclusions are presented in Section V.

II. ANALYSIS

A down-converting FOL (Fig. 1), employing a pair of serially cascaded, quadrature-biased, Mach-Zehnder interferometric modulators is analyzed here. We first present expressions for evaluating the conversion loss of the link for conversion of RF to an IF. We then develop expressions for evaluating link sensitivity. In this context we present expressions for the noise figure and minimum detectable signal. These are both important parameters that characterize the sensitivity of the FOL. The intermodulation-distortion performance of a Mach-Zehnder interferometric modulator has been previously addressed [10]–[11] and hence will not be discussed here.

A. Conversion Loss of the FOL

For a pair of quadrature-biased Mach-Zehnder interferometric modulators cascaded in series, the output optical power (P_0) at the PD, in terms of the input optical power (P_{in}) into the interferometer, is given by [10]

$$\begin{aligned}P_0 =& \frac{T_D P_{in}}{4}\\ &\cdot \left(1 - sin\left[\frac{\pi V_{RF}}{V_{\pi RF}(f_{RF})} sin(\omega_{RF}t + \theta(\omega_{RF}))\right]\right)\\ &\cdot \left(1 - sin\left[\frac{\pi V_{LO}}{V_{\pi LO}(f_{LO})} sin(\omega_{LO}t + \theta(\omega_{LO}))\right]\right)\end{aligned} \tag{1}$$

where $V_{RF} sin\omega_{RF}t$ and $V_{LO} sin\omega_{LO}t$ are the input ac electrical signals applied to the RF and LO modulators, respectively, and $V_{\pi RF}(f_{RF})$ and $V_{\pi LO}(f_{LO})$ are the frequency dependent half-wave voltages ($V_\pi(f)$) [12] of the RF and LO modulators at the respective modulation frequencies; the magnitude of the frequency dependent roll-off of the modulators is contained in $V_\pi(f)$, and the phase of the response is contained in $\theta(\omega)$. T_D represents the coupling and optical transmission losses of the FOL with the interferometer biased for maximum transmission. Expanding the above equation in terms of Bessel functions and dropping third and higher order terms, we get

$$\begin{aligned}P_0 =& \frac{T_D P_{in}}{4}(1 - 2J_1(X_{RF}) sin[\omega_{RF}t + \theta(\omega_{RF})]\\ &- 2J_1(X_{LO}) sin[\omega_{LO}t + \theta(\omega_{LO})]\\ &+ 2J_1(X_{RF})J_1(X_{LO}) cos[(\omega_{LO} - \omega_{RF})t\\ &+ \theta(\omega_{LO}) - \theta(\omega_{RF})]\\ &- 2J_1(X_{RF})J_1(X_{LO}) cos[(\omega_{LO} + \omega_{RF})t\\ &+ \theta(\omega_{LO}) + \theta(\omega_{RF})])\end{aligned} \tag{2}$$

where $X_{RF} = \frac{\pi V_{RF}}{V_{\pi RF}(f_{RF})}$, $X_{LO} = \frac{\pi V_{LO}}{V_{\pi LO}(f_{LO})}$ and J_n is the Bessel function of order n. In the above equation, the contribution of the dc term (P_{DC}) to the optical power at the photodetector is given by $P_{DC} = \frac{T_D P_{in}}{4}$. If R is the responsivity of the photodetector, then the total detected dc photocurrent $I_{DC} = \frac{R T_D P_{in}}{4}$. At an angular difference frequency of $\omega_{LO} - \omega_{RF}$ (IF) the electrical power delivered to a 50 Ω load is given by

$$P(\omega_{LO} - \omega_{RF}) = \frac{I_{DC}^2}{2}(2J_1(X_{RF})J_1(X_{LO}))^2 \cdot 50. \tag{3}$$

If P_{RF} is the input signal power applied to the RF modulator (with V_{RF} being the corresponding ac voltage into a 50-Ω load), the conversion loss (CL) of the down-converting FOL is given by

$$CL = \frac{P(\omega_{LO} - \omega_{RF})}{P_{RF}}. \tag{4}$$

B. Sensitivity

As illustrated in Fig. 1 the down-converting FOL is comprised of the laser, the modulators, the Erbium-doped fiber amplifier (EDFA), and the PD's. Hence the total output noise at the PD's includes, in addition to input noise, contributions from the laser's relative intensity noise (RIN), the EDFA's amplified-spontaneous-emission (ASE) noise, and the PD's thermal and shot noise. It has been shown [13] that the noise of a laser amplified by an EDFA is similar to that of a laser with an effectively higher RIN. Hence in the analysis of output noise presented below, the noise sources considered are the system's input noise, the PDs' thermal and shot noise, and an effective laser RIN, which is assumed to include the EDFA's added noise. Then the total output noise (N_{out}) of the FOL is given by

$$N_{out} = kTB \cdot CL + kTB \cdot CL \cdot \frac{P_{RF}}{P_{LO}} + 4kTB + 2qI_{DC}R_LB + RIN(f) \cdot I_{DC}^2 R_L B \qquad (5)$$

where P_{LO} is the pump signal applied to the LO modulator. The first two terms on the right-hand-side (RHS) of the above equation correspond to the systems's input noise modified by conversion losses associated with the RF and LO inputs, both of which are assumed to be thermal noise limited. The third term corresponds to detector thermal noise [14]. The last two RHS terms correspond to shot and RIN noise sources, respectively. k is Boltzmann's constant, $T = 300^0$ K is the noise temperature, B is the receiver bandwidth ($=$ 1 Hz in the data and analyses presented in this paper), q is the electronic charge, R_L is the load resistance ($=$ 50 Ω), and $RIN(f)$ is the effective laser RIN. The noise figure (NF) of the link is given by

$$NF = \frac{N_{out}}{CL \cdot kTB}. \qquad (6)$$

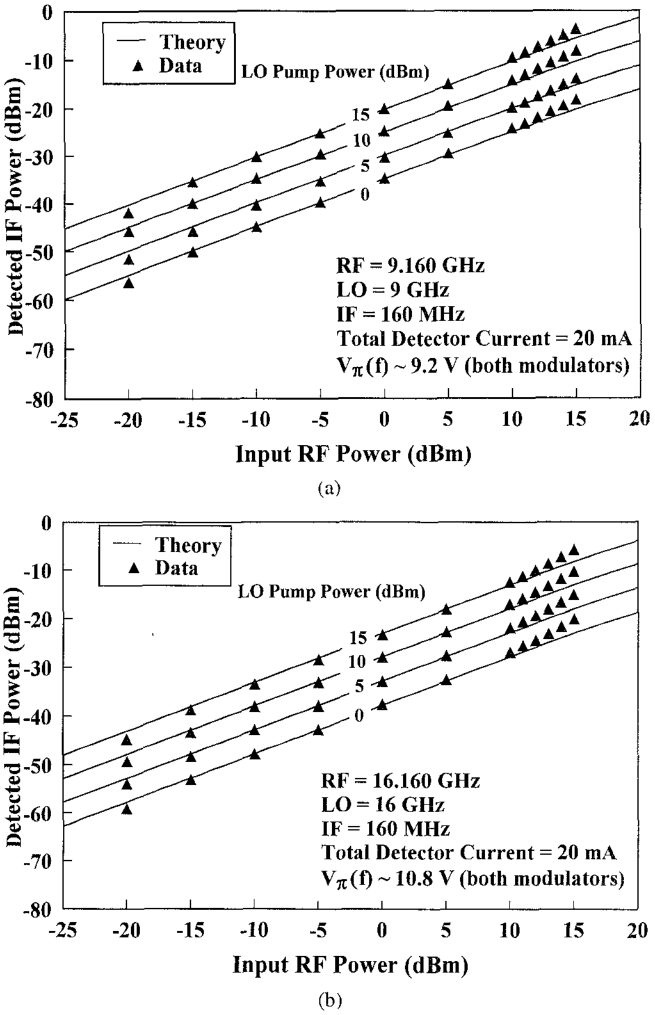
For application of the FOL in sensor systems, an important system parameter that characterizes link sensitivity is the minimum detectable signal (MDS). This parameter specificies the amplitude of the smallest signal that can be detected so that output signal is 3 dB above the noise floor [15]. However, in some radar systems, a larger signal-to-noise margin is required at the output to increase the probability of detection and to lower the false alarm rate. In such systems, MDS is specified at a level where the output signal is 10–16 dB above the noise level [15]. In the analysis presented in this paper, we define MDS as the smallest detectable RF signal for which down-converted IF signal is 3 dB above the output noise level. Thus MDS is given by

$$MDS = 2 \cdot kTB \cdot NF. \qquad (7)$$

In the above equation the factor 2 in the RHS, allows for, per definition, the 3-dB output signal-to-noise ratio requirement.

III. Experiments

The operation of the down-converting FOL may be explained with reference to Fig. 1. The RF signal to be sensed is applied to the first optical modulator. The modulated optical signal is then transmitted over a polarization preserving fiber (PPF) to the second modulator, to which an LO pump signal is applied. The output of the second modulator is optically amplified with an EDFA. To avoid power saturation of the low-speed PD, we employed a 3-dB optical splitter to divide the amplified optical signal. The split signals were then detected by a pair of PD's operating in parallel. The outputs of these PD's were electrically power combined and fed into the spectrum analyzer where the detected IF was measured. To the best of our knowledge, this is the first demonstration of power-combining of PD's in a signal processing application as a means to circumvent PD saturation. Concurrently, this technique also allows for a reduction in the conversion loss of the link.



(a)

(b)

Fig. 2. CL performance of the down-converting link for a total detector current of 20 mA at RF carrier frequencies of (a) 9.16 and (b) 16.16 GHz. A 50-Ω load resistance was assumed in the model.

For the experiments reported here link performance was evaluated for two different 1.5 μm laser sources: an OKI diode laser and an AMOCO diode pumped solid state laser (RIN ≈ −165 dB/Hz). The modulators (Ti:LiNbO$_3$ traveling wave design) were developed in-house [12], [16], and were packaged with PPF pigtails at both ends. The EDFA was assembled in-house. The length of the Er^{3+}-doped fiber was 10 m. The fiber was counter-directionally pumped with a 980-nm laser via a wavelength division multiplexer (WDM). Two optical isolators were employed at either end of the EDFA to prevent the onset of lasing. The EDFA exhibited a gain of ≈ 22 dB with a saturated output power of ≈ 14 dBm. The PD's employed were EPITAXX ETX 75FJ whose responsivity and 3-dB bandwidth were specified to be 0.85 A/W and 2 GHz, respectively. These PD's were pigtailed with multi-mode fibers. Since our chosen IF frequency was 160 MHz, the 2-GHz PD bandwidth was more than adequate. The electrical RF and LO inputs to the modulators were obtained from synthesized sources which were locked to a 10-MHz reference signal.

Fig. 2(a) illustrates the conversion loss performance of the downconverting link for RF and LO signals near 9 GHz with the IF at 160 MHz; the total PD current I_{DC} (from the detector

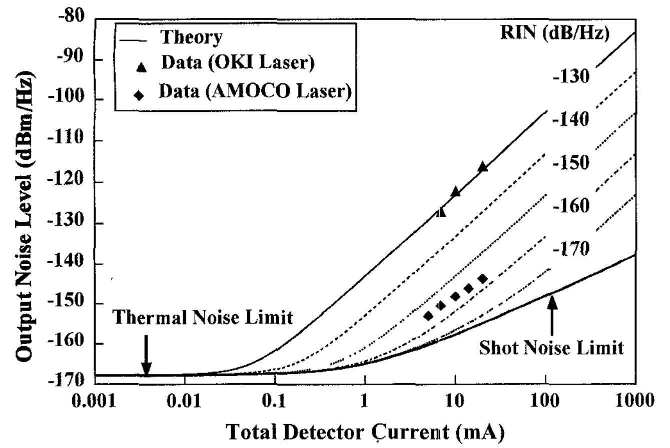
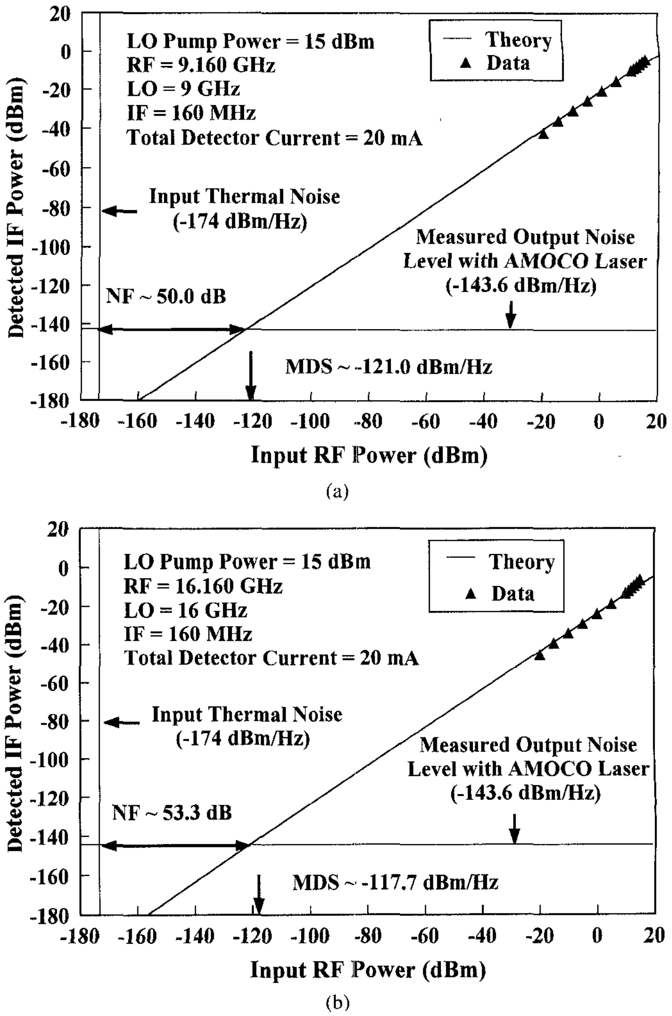


Fig. 3. Modeled and measured FOL IF output noise levels as a function of total detector current I_{DC} for different levels of laser RIN. Model assumes the following: 50-Ω detector load resistance, LO pump power = 15 dBm, and $V_{\pi}(f) = 5$ V.

pair) was ≈ 20 mA. As shown, the detected IF output signal varies linearly with both input RF and LO pump powers. The measured CL for a LO pump power of +15 dBm was ≈ 19.6 dB, which is nearly 40 dB better than what we previously reported [10]. Also, as shown, the data is in good agreement with theoretical predictions. At 9 GHz the $V_{\pi}(f = 9 \text{ GHz})$ for each modulator was ≈ 9.2 V. For the same total PD current ($I_{DC} \approx 20$ mA), we show in Fig. 2(b) the performance of the downconverting link for RF and LO signals near 16 GHz with the IF at 160 MHz. The measured CL in this case for a LO pump power of +15 dBm was ≈ 22.9 dB, and $V_{\pi}(f = 16 \text{ GHz})$ for each modulator was ≈ 10.8 V. We attribute the larger CL and $V_{\pi}(f)$ at 16 GHz to roll-off in the frequency response of the modulator. We note here that CL is independent of the type of laser source employed. Although not shown, the measured input SWR of the link was better than 2 over the dc-18 GHz frequency span indicating that the modulators were well matched to 50 Ω.

The measured output IF noise level of the link as a function of total PD current is shown in Fig. 3 for both laser sources. The computed results from (5) are also shown in the same figure for different levels of effective laser RIN. These measurements indicate that the output noise was RIN limited, and the effective RIN level was ≈ −130 dB/Hz for the OKI laser and ≈ −157 dB/Hz for the AMOCO laser.

The NF and MDS of the link employing the AMOCO laser may be determined from Fig. 4. As shown in Fig. 4(a), at RF and LO frequencies near 9 GHz, for a 20 mA total PD current, and the NF and MDS of the down-converting FOL are measured to be 50 dB and −121 dBm/Hz, respectively. At 16 GHz, as shown in Fig. 4(b), the measured NF and MDS degrade to 53.3 dB and −117.7 dBm/Hz, respectively, due to roll-off in the frequency response of the modulator. The results of these experiments are summarized in Table I for two different total detector currents (10 and 20 mA). As shown, even when the total detector current was increased from 10–20 mA, the NF and MDS of the link remain relatively unchanged. This is due to the fact that the output noise was limited by the effective laser RIN. This will be discussed in better detail in the next section.



(a)

(b)

Fig. 4. Performance of the down-converting link for a total detector current of 20 mA. The noise figure (NF) and minimum detectable signal (MDS) are shown at RF carrier frequencies of (a) 9.16 GHz and (b) 16.16 GHz. A 50-Ω detector load resistance was assumed in the model.

IV. Discussion

The sensitivity of a down-converting FOL is critically dependent on the signal-to-noise ratio at the output. Here, the signal level is determined by the conversion loss, and the output noise level is set by the different noise sources. In Section III we have clearly demonstrated how conversion loss may be decreased by employing optical amplification in conjunction with power combining of PD's. But, as summarized in Table I, even though the conversion loss is improved in increasing the total detector current from 10 to 20 mA, the NF and MDS remain relatively unchanged. This is due to the fact that the output noise of the link was limited by the effective laser RIN. The output noise level may be further decreased by employing a laser with an even lower RIN, and by optimizing the EDFA to reduce ASE noise. Alternately, laser noise can also be cancelled using techniques such as balanced detection [17]–[18], allowing for shot-noise-limited operation of the down-converting FOL.

TABLE I
SUMMARY OF THE CONVERSION LOSS, NOISE FIGURE (NF) AND MINIMUM DETECTABLE SIGNAL (MDS) OF THE LINK FOR DIFFERENT DETECTOR CURRENTS AT DIFFERENT CARRIER FREQUENCIES. THE AMOCO LASER WAS EMPLOYED TO OBTAIN THESE RESULTS

Frequency (GHz)	Detector Current (mA)	Conversion Loss (dB)	NF (dB)	MDS (dBm/Hz)
9	10	24.1	50.1	-120.9
16	10	29.4	55.4	-115.6
9	20	19.6	50.0	-121.0
16	20	22.9	53.3	-117.7

If laser noise is either negligibly small or can be cancelled with balanced detection, the output noise of the link would be shot noise limited. Under this condition the signal-to-noise ratio at the output (and hence NF and MDS) can be significantly improved by increasing the optical power on the detector. This is because the signal is proportional to the square of the detector current, whereas shot noise is proportional to just the detector current. Assuming that the total output noise of the link is a sum of detector thermal noise and shot noise, we will now estimate link performance; these calculations assume a 50 Ω detector load resistance, and a LO modulator modulation depth of 100%. We show in Fig. 5 the calculated output IF signal level as a function of average total detector current for an assumed RF input signal strength of −150 dBm; calculations are shown for different values of $V_\pi(f)$. We also show (on the same scale along a different y-axis) the variation of output noise as a function of total detector current. In this figure, detectable signals correspond to output IF signal levels that are 3 dB above the output noise. As shown, in the shot noise limit, the output signals increase more rapidly (as expected) with total detector current than does output noise; IF signal levels above −150 dBm correspond to conversion gain, and those below −150 dBm correspond to conversion loss. Fig. 5 clearly illustrates how total PD current and $V_\pi(f)$ factor into link sensitivity. It would now be of interest to study how the total PD current and $V_\pi(f)$ affect MDS. This information is available in Fig. 6. Here we plot the calculated MDS as a function of total detector current for different values of $V_\pi(f)$. From this figure, for a total detector current near 50 mA (which is possible with PD power combining), with $V_\pi(f) \approx 5$ V we predict a MDS near −147 dBm/Hz. This figure illustrates that if the output noise were shot noise limited, then very weak signals can be detected if low $V_\pi(f)$ modulators are employed in conjunction with optical amplification to obtain a large (tens of mA) total PD current obtainable through power combining of detectors.

Down-conversion detection employing serially cascaded modulators is intrinsically suited for antenna remoting applications. Here the RF and LO modulators can be placed in remote locations with high isolation between their signal ports. Also, since the IF is generated at the PD it cannot electrically couple into the RF or LO ports. Since modulators with performance from dc–75 GHz have been recently reported [19], the technique advanced here can easily be scaled to detect such frequencies. Furthermore, compared to optical heterodyne detection, down-conversion detection has the following advantage: Optical heterodyne detection may be limited by the frequency stability of the PLL. For frequencies above 2 GHz the rate at which the output frequency of a laser can be tuned is presently limited by a relatively slow piezoelectric or thermal tuning process. In contrast, in down-conversion detection with cascaded modulators, very stable, rapidly tunable voltage-controlled oscillators (VCO's) can be employed as LO sources.

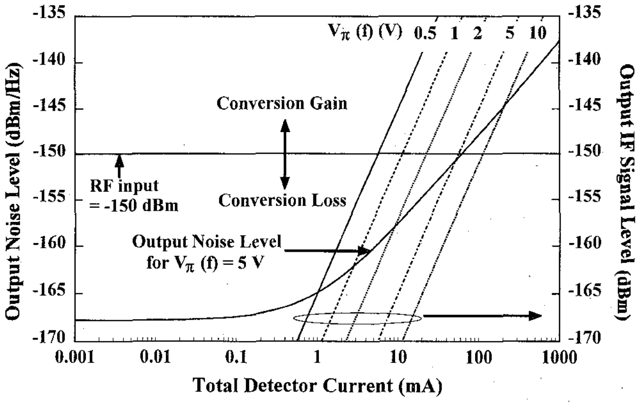


Fig. 5. Calculated output noise level (assuming detector thermal and shot noise) and output IF signal level (for −150 dBm RF input) as a function of total detector current. The output signal level (for −150 dBm RF input) is plotted for different values of $V_\pi(f)$. Output signal levels above −150 dBm indicate conversion gain and below −150 dBm indicate conversion loss. Model assumes a 50 Ω detector load resistance and a LO modulator modulation depth of 100%.

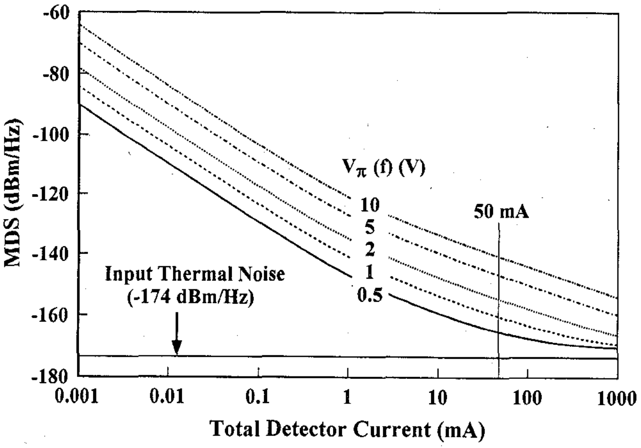


Fig. 6. Calculated minimum detectable signal (MDS) as a function of total detector current for different values of $V_\pi(f)$. Output noise was estimated assuming detector thermal and shot noise. Model assumes a 50 Ω detector load resistance and a LO modulator modulation depth of 100%.

V. CONCLUSION

We have demonstrated a FOL for concurrent detection and downconversion of microwave signals. Optical amplification in conjunction with low $V_\pi(f)$ modulators and electrical power combining of PD's has made possible the realization of very low link losses; the conversion losses demonstrated here are ≈ 40 dB better than previously reported. To the best of our knowledge, this is the first demonstration of power combining of PD's as means to circumvent PD saturation; concurrently this technique also allows for the conversion loss of the FOL to be improved. The low values of MDS demonstrated here, coupled with the cascaded modulators architecture (which is intrinsically suited for antenna remoting applications), allows for application of the downconverting FOL in practical broadband sensor systems. Further improvements in link sensitivity is obtainable either through balanced detection or by employing a low RIN laser in conjunction with an EDFA optimized for a low noise figure.

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REFERENCES

[1] C. H. Cox, "High-performance fiber-optic links for microwave applications," in *1993 IEEE Int. Microwave Symp. Dig.*, 1993, pp. 719–722.

[2] C. H. Cox, G. E. Betts, and L. M. Johnson, "An analytic and experimental comparison of direct and external modulation in analog fiber-optic links," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 501–509, 1990.

[3] A. S. Daryoush, E. Ackerman, N. Samant, S. Wanuga, and D. Kasemset, "Interfaces for high-speed fiber-optic links: analysis and experiment," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 2031–2044, 1991.

[4] J. E. Bowers, A. C. Chipaloski, and S. Boodaghians, "Long distance fiber-optic transmission of C-band microwave signals to and from a satellite antenna," *J. Lightwave Technol.*, vol. 5, pp. 1733–1741, 1987.

[5] R. Olshansky, V. Lanzisera, and P. Hill, "Subcarrier multiplexed lightwave systems for broadband distribution," *J. Lightwave Technol.*, vol. 7, pp. 1329–1342, 1989.

[6] T. E. Darcie, "Subcarrier multiplexing for lightwave networks and video distribution systems," *IEEE J. Select. Areas Commun.*, vol. 8, pp. 1240–1248, 1990.

[7] R. D. Esman, M. Y. Frankel, J. L. Dexter, L. Goldberg, M. G. Parent, D. Stilwell, and D. G. Cooper, "Fiber-optic prism true time-delay antenna feed," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 1347–1349, 1993.

[8] K. J. Williams and R. D. Esman, "Observation of photodetector nonlinearities," *Electron. Lett.*, vol. 28, pp. 731–732, 1992.

[9] R. T. Logan, Jr. and E. Gertel, "Millimeter-wave photonic downconvertors: Theory and demonstrations," accepted for presentation at *SPIE Conf. Optical Technology for Microwave Applications VI*, July 1995.

[10] G. K. Gopalakrishnan, W. K. Burns, and C. H. Bulmer, "Microwave-optical mixing in $LiNbO_3$ modulators," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 2383–2391, 1993.

[11] B. H. Kolner and D. W. Dolfi, "Intermodulation distortion and compression in an integrated electrooptic modulator,"*Applied Opt.*, vol. 26, no. 17, pp. 3676–3680, 1987.

[12] G. K. Gopalakrishnan, W. K. Burns, R. W. McElhanon, C. H. Bulmer and A. S. Greenblatt, "Performance and modeling of broadband $LiNbO_3$ traveling wave optical intensity modulators," *J. Lightwave Technol.*, vol. 12, pp. 1807–1819, 1994.

[13] A. Cavaciuti and B. Sordo, "Noise Measurements in EDFA's," in *OFC Tech. Dig.*, 1994, paper WM9.

[14] A. B. Carlson, *Communication Systems*. New York: McGraw-Hill, 1975.

[15] K. Chang, *Microwave Solid-State Circuits and Applications*. New York: Wiley, 1994.

[16] G. K. Gopalakrishnan, C. H. Bulmer, W. K. Burns, R. W. McElhanon, and A. S. Greenblatt, "40 GHz low half-wave voltage $Ti:LiNbO_3$ intensity modulator," *Electron. Lett.*, vol. 28, no. 9, pp. 826–827, 1992.

[17] A. Yariv, *Quantum Electronics*, 3rd ed. New York: Wiley, 1989, p. 442.

[18] G. L. Abbas, V. W. Chan, and T. K. Yee, "A Dual-detector optical heterodyne receiver for local oscillator noise suppression," *J. Lightwave Technol.*, vol. 3, pp. 1110–1122, 1985.

[19] K. Noguchi, H. Miyazawa, and O. Mitomi, "75 GHz broadband $Ti:LiNbO_3$ optical modulator with ridge structure," *Electron. Lett.*, vol. 30, pp. 949–950, 1994.

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