Reduced Loss Microwave Fiber-Optic Links by Intracavity Modulation and Carrier Suppression

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***Abstract*— Fiber-optic links are limited by the large V_π of commercial modulators and by nonlinearities in the photodiodes used to demodulate the RF signals. Intracavity modulation and carrier suppression is shown to enhance the received microwave power in a fiber-optic link for a given optical power at a receiver. The carrier wavelength is automatically locked to the intracavity reflective notch filter that suppresses the carrier relative to the modulation sidebands. Link loss reductions exceeding 10 dB were measured for frequencies from 1 to 25 GHz. Harmonic distortions can be decreased by combining this technique with above-quadrature biasing.**

***Index Terms*—Fiber-optic links, carrier suppression.**

I. Introduction

The use of fiber-optic links (FOL's) for carrying microwave signals has shown great potential. The nearly lossless transmission of RF-modulated optical signals over fibers can simplify the design of a communication link, in which it is undesirable to carry the RF signals via microwave cables. Optical signals can also be easily amplified to provide RF amplification out of the demodulating (optical-to-RF) photodetector. Microwave FOL loss is, however, limited by the optical carrier modulation depth that can be imposed for a given input RF signal and the maximum incident optical power on the photodetector without excessive nonlinearities [1]–[3] or damage [4]. With current commercial InGaAs p-i-n photodiodes and $LiNbO_3$ traveling wave modulators, the net RF link loss at 1550 nm is typically 40 dB.

One way to reduce the microwave loss in a FOL, given current device limitations, is through optical carrier suppression (CS) [5], [6]. The effective modulation depth is increased by CS while the carrier power is reduced. Subsequent optical amplification up to the average power limit of the photodetector reduces the RF link insertion loss. Undesirable second harmonics are introduced by CS at the output of the link, even when the modulator is biased at quadrature. However, for some applications, such as octave bandwidth systems or small modulation depth systems, the second-order terms are acceptable [5].

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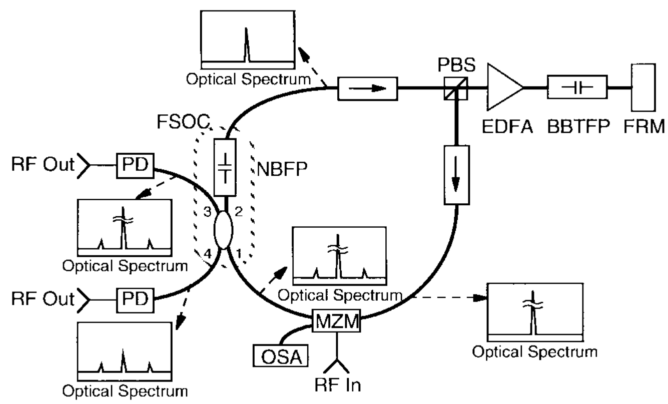

Fig. 1. Modified "σ laser" used in the experiment. All components to the left of the PBS are pigtailed with polarization-maintaining fiber, and all components to the right of the PBS are pigtailed with single-mode fiber. The inset optical spectra show the relative powers in the carrier and sidebands at various points within and external to the laser.

Carrier suppression can be implemented by sending the modulated optical signal through a "notch" filter that attenuates the carrier wavelength more than the modulation sidebands. This technique has been demonstrated at a single frequency [5] and in a wideband [6] system with a reduction in RF link loss of 13 dB. However, both of these systems suffered the that fact that the filter and the laser required precise wavelength matching. Relative drifts in the carrier and filter wavelengths introduced substantial gain instabilities. The control circuitry required to reduce the wavelength drifts would increase the complexity of any system.

II. Design

We propose and demonstrate a CS system that minimizes relative drifts between the carrier and filter wavelengths. The idea is illustrated in Fig. 1. A ring laser cavity is used with an intracavity optical modulator and a frequency-selective output coupler (FSOC). The FSOC is a device that maximally transmits light at frequency ω_0 and maximally couples light out of the cavity for frequencies outside the narrow passband centered around ω_0. For frequencies within the passband, even at ω_0, some light is still coupled out, but is attenuated relative to the frequencies outside the passband. A 3-dB coupler followed by a Fabry–Perot filter can function as an FSOC, since it possesses the transmission and reflection characteristics described above [7]. The inset optical spectra at various points within the cavity show that the optical field emerging from the FSOC has an attenuated carrier field but essentially unattenuated sideband fields. After demodulation by a photodetector, the dc photocurrent is reduced more than the RF photocurrent. Optical amplification to the maximum dc photocurrent results in a net RF gain as compared to the case with the same dc photocurrent without CS. Since the optical field that is transmitted through the FSOC is amplified by the gain media, the laser always oscillates at the center frequency of the FSOC. Drift of the FSOC passband is automatically tracked by the carrier frequency, as long as the drifts remain within the gain bandwidth of the amplifier, without the need for external control for locking the laser and filter wavelengths.

The laser design shown in Fig. 1 is a slight modification of a "σ-laser" [8], [9]. All elements in the loop are pigtailed with polarization-maintaining fiber. The elements in the straight segment are pigtailed with single-mode fiber. The Er-doped fiber amplifier (EDFA) consisted of 50 cm of $\sim$2000 ppm erbium-doped fiber pumped by an 80-mW, 980-nm laser diode. The Faraday rotator mirror (FRM), combined with the polarizing beamsplitter (PBS), provides stable linear polarization within the loop section of the cavity. The FSOC was composed of a 3-dB coupler and a narrow-band Fabry–Perot filter (NBFP), having a free spectral range (FSR) of $\sim$100 GHz and a bandpass of $\sim$500 MHz. Wavelength tuning between NBFP transmission peaks was provided by a broadband, tunable Fabry–Perot filter (BBTFP), which had a $\sim$60-nm FSR and a 0.4-nm bandpass. Optical isolators were necessary on both sides of the PBS, to prevent parasitic laser oscillation due to the large back reflections from the NBFP. The 16-GHz $LiNbO_3$ dual output, Mach–Zender modulator (MZM) had a $V_\pi \cong 16$ V. The output from Port 4 of the coupler provided the carrier- suppressed signal, while Port 3 allowed monitoring of the directly modulated signal.

The wavelength was selected by tuning the BBTFP to coincide with a transmission peak of the NBFP. By changing the voltage applied to the BBTFP, the laser wavelength could be changed in $\sim$0.8-nm increments, corresponding to the FSR of the NBFP. Near the peak of the Er gain profile, approximately 0.3 mW could be coupled out at Port 3.

III. Experiment

The modulator was biased to quadrature. The output from Port 3 of the FSOC was incident on the photodiode (PD), and the RF frequency response and the dc photocurrent were recorded. A typical RF spectrum is shown by Trace A in Fig. 2 and provided a reproducible reference response of a conventional FOL. Next, without changing the operating conditions of the laser, the output from Port 4 of the FSOC was coupled to the PD. Again, both the RF frequency response and dc photocurrent were recorded. Due to the laser instabilities, this frequency spectrum varied from sweep to sweep. An average of six separate frequency sweeps was taken and is shown as Trace B in Fig. 2, along with error bars to show the typical trace to trace variations. Both traces show similar spectral characteristics, determined by the RF characteristics of the modulator and photodetector.

Our system suffered from laser instabilities. The laser mode beating characteristics, observed on an RF spectrum analyzer,

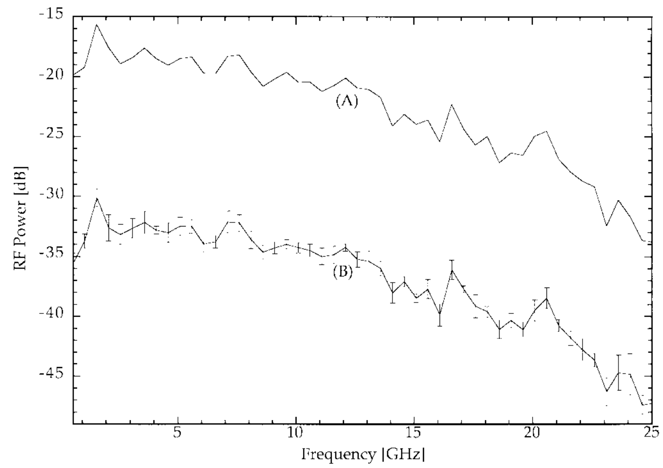

Fig. 2. Measured fiber-optic link efficiency. Trace A shows the link response from port 3 of the coupler, which is not filtered. Trace B shows the link response from port 4 of the coupler that has been filtered by the FSOC. The error bars on Trace B show the typical variation for different frequency sweeps.

indicated that the unmodulated laser contained between five and ten longitudinal cavity modes, spaced by $\sim$10 MHz. The laser output fluctuated between numerous mode configurations, rarely lasing in any particular group of modes for more than 1 s. Consequently, the average power reflected from the NBFP varied by 1–3 dB over several seconds, whereas the average power within the cavity, i.e., incident on the NBFP, fluctuated by only 0.2–0.4 dB within a similar time period. The reason for this is suspected to be that each laser mode has a slightly different transmission through the FSOC. Although the transmission may change by only 4%, say from 92% to 96%, over the range of modes observed, this corresponds to a change in reflectivity from 8% to 4% (a 3-dB decrease in the reflected signal). Thus, the average recirculating power was relatively constant, whereas the average carrier-suppressed power varied considerably. These large fluctuations in the reflected dc carrier power also produced similar fluctuations in the demodulated RF power. We reduced the variations from this effect by averaging the RF power at each frequency during each frequency sweep and then taking an average over several sweeps.

The PD operated in a linear regime, so the RF spectra for the directly modulated signal and the carrier-suppressed signal were compared by simply normalizing each spectra by its average photocurrent. This would be equivalent to amplifying the optical powers to the same average levels. The result of this analysis is shown in Fig. 3. Carrier suppression yields a nearly constant 10.2 ± 0.1 dB increase in the received RF power for all frequencies above 1 GHz. This enhancement corresponds to effectively lowering the modulator V_π from 16 to 4.9 V. The measured reduction in link loss is nearly equal to the 12-dB reduction one would expect from the residual carrier reflection ($\sim$6%) of the NBFP. Below 2 GHz the FSOC reflectivity begins to decrease, which explains the decreased link loss reduction we observed in this frequency range.

By designing the laser to oscillate with a single longitudinal mode (SLM), the instability of the RF frequency response is

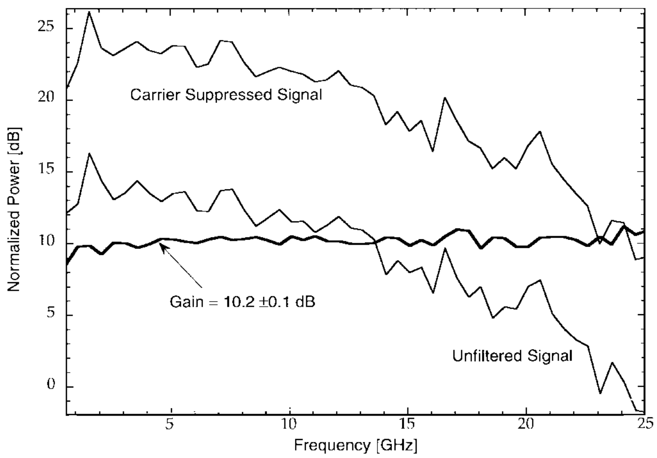

Fig. 3. Carrier suppressed signal and the directly modulated signal, each normalized by the dc power received at the photodetector. The enhancement of 10.2 ± 0.1 dB in RF power (shown by the thick line) is nearly constant for frequencies from 2 to 25 GHz. Below 2 GHz, a small decrease in the RF signal is observed due to the reduced reflection from the $\sim$500-MHz bandwidth FSOC.

expected to diminish. The multimode nature of our present design is due primarily to the large round trip loss through the cavity. Using components with less loss will facilitate single mode operation. This could also be achieved by including the FSOC and modulator within an all PM fiber SLM ring laser [10]. A larger reduction of link loss is expected for a SLM laser, since the reflected carrier for a single longitudinal mode will be less than for the present multimode case, while the modulation sidebands will be essentially the same magnitude.

As mentioned above, CS has the drawback of introducing second harmonics, as well as other second-order intermodulation distortion terms. For suboctave applications, the third-order distortion products are dominant. In such cases, CS increases the spur-free dynamic range (SFDR) and reduces the link loss. For applications where second-order distortion terms are important, numerical analysis [6] shows that we can combine off-quadrature biasing (OQB) with CS to reduce the magnitude of the induced second-order terms relative to the fundamental. Biasing away from quadrature, however, decreases the enhancement of the fundamental frequency that can be obtained through CS at quadrature. A tradeoff exists between link loss reduction and second harmonic content when combining OQB and CS. Calculations show that with 1% carrier reflection and biasing 55° above quadrature, a 10-dB reduction in link loss results (at the fundamental frequency) with no reduction in SFDR as compared to a link without any CS, biased at quadrature, and an identical received average optical power. For suboctave applications, a 20-dB link loss reduction and an increase of $\sim$7 dB Hz$^{2/3}$ in SFDR would be obtained (assuming a photocurrent of 1 mA into 50 Ω). It should also be noted that even without any carrier suppression small deviations from biasing at quadrature $(<1^\circ)$ also introduce second-order distortions. Thus, the second-order distortions that result from CS may not, in practice, impair the link dynamic range significantly more than the requirement of maintaining exact biasing at quadrature [11].

IV. Conclusion

In conclusion, we have demonstrated a technique for reducing the loss of a microwave fiber-optic link. Previously observed difficulties due to the relative drift between the carrier and filter frequencies are reduced with this new method, since the carrier and filter frequencies are locked to each other within the laser resonator. A constant reduction in link loss of over 10 dB was produced for microwave frequencies from 1–25 GHz. Our system performed equally well within the $\sim$10-nm range for which laser output was observed. The range of frequencies for which our method can be extended is limited only by the FSR and finesse of the NBFP and the bandwidth of the modulator. Single longitudinal mode operation of laser ring cavity is expected to provide for more stable output and a larger microwave power enhancement.

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