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Power Penalty From Amplified Spontaneous Emission in Spatial Diversity Links for Fade Mitigation

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***Abstract*—We investigate the power penalty caused by excess amplified spontaneous emission in an optically preamplified receiver for a communications link where a multiwavelength spatial diversity transmitter is used to mitigate atmospheric fading. We compare measured receiver sensitivity for a four-wavelength 10.7-Gb/s nonreturn-to-zero on–off-keyed system to theory using both the Gaussian noise approximation and chi square statistics.**

***Index Terms*—Diversity methods, fading channels, optical amplifiers, optical receivers.**

I. INTRODUCTION

THE USE of multiple, spatially diverse beams is a well-known method of mitigating scintillation in optical links where the dominant effect is turbulence in the near field of the transmitter [1]–[10]. To transmit information, multiple beams are imparted with identical data modulation and launched through individual telescope apertures or subapertures. The path lengths from the data modulators to the apertures must be matched to within a small fraction of a bit period to synchronize the bits across the different beams. The multiple apertures are physically separated by a distance that is large compared to the atmospheric coherence length $r_{\rm o}$ so that each beam experiences independent turbulence conditions as it propagates through the atmosphere. Thus, the beams produce different time-varying profiles that overlap in the far field, each resulting in a unique scintillation pattern at the receiver aperture. The beams are incident on a common photodetector, and the penalty associated with the deep fade of any one beam is minimized because the fades of the different beams are uncorrelated. The probability of a deep fade with multiple beams is the joint probability of simultaneous deep fades on all beams, an event with a dramatically lower probability than a deep fade on a single beam. Spatial diversity techniques can be used in conjunction with coding and interleaving to provide robust communications performance; however, by actually reducing the scintillation variance, spatial diversity alleviates requirements on clock recovery and spatial tracking systems, whereas temporal diversity techniques alone do not.

The spatially separated beams must also be separated in wavelength to avoid baseband beat products within the electrical bandwidth of the square-law photoreceiver. The optical filter in the receiver must be wide enough to accommodate all of the beams, with an associated penalty in receiver sensitivity caused by the additional optical noise passed by the wider filter. Thus, the spatial diversity technique provides fade mitigation at the expense of a receiver penalty relative to the sensitivity achieved using optimal filtering with a single beam. Wavelength spacings and filter bandwidths are selected to minimize penalties caused by both the baseband beat products and optical noise.

Here, we investigate the power penalty associated with the wider optical filter necessary to accommodate multiple wavelengths from a spatial diversity transmitter. We measure optically preamplified receiver sensitivity as a function of optical filter bandwidth for a 10.7-Gb/s nonreturn-to-zero (NRZ) on–off keyed (OOK) link, and compare to theory using both the Gaussian noise approximation and chi square statistics. The results are in excellent agreement with theory for both a single-wavelength link and a link with four wavelengths spaced by three times the data rate, and show that even with an optical filter as wide as 800 GHz, the power penalty for a given modulator extinction ratio can be limited to ~4.6 dB at a bit-error rate (BER) of 10^{-4} without a polarization filter.

II. THEORY

Using the Gaussian noise approximation, we extend the standard Q-factor analysis [11]–[14] to the multiwavelength case by assuming that each wavelength carries identical modulation and that the wavelengths are sufficiently separated so that baseband beating of adjacent wavelengths is negligible within the bandwidth of the receiver. We then find the average power required to maintain a constant Q as the optical filter bandwidth is varied. We assume an optically preamplified receiver with ideal rectangular filters where 1) the signal × amplified spontaneous emission (ASE) and ASE × ASE noise terms dominate over the shot noise and receiver electronics noise, and 2) the optical filter bandwidth B_o is greater than or equal to twice the electrical filter bandwidth B_e. Following the approach in [14] for NRZ OOK with a finite modulator extinction ratio defined by $\varepsilon = P_{\rm zero}/P_{\rm one}$, we find an analytic expression for the receiver sensitivity

$$N = Q\beta\frac{n_{\rm sp}(G-1)B_e}{\eta_{\rm in}G}\left[2Q\beta+\sqrt{\frac{p(2B_o-B_e)}{B_e}+\frac{16Q^2\varepsilon}{(1-\varepsilon)^2}}\right] \tag{1}$$

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where

$$\beta \equiv \frac{1+\varepsilon}{1-\varepsilon}. \tag{2}$$

Here, N is the number of signal photons received per second $(N = P_{\rm rcvd}/h\nu)$, $\eta_{\rm in}$ is the coupling efficiency from the input fiber to the amplifier, G is the amplifier gain, q is the electronic charge, $n_{\rm sp}$ is the spontaneous emission factor of the amplifier, and p is the number of ASE polarization modes supported by the receiver.

The Gaussian approximation yields a convenient analytical expression; however, in the limit where the signal × ASE and ASE × ASE terms dominate, the noise statistics are more accurately described by a noncentral chi square distribution [15]

$$f_E(x) = \frac{1}{N_o}\left(\frac{x}{E}\right)^{(M-1)/2} \exp\left(-\frac{x+E}{N_o}\right) I_{M-1}\left(2\frac{\sqrt{xE}}{N_o}\right) \tag{3}$$

where E is the amplified bit energy, $N_o = n_{\rm sp}(G-1)$ is the amplitude of the noise spectral density (normalized to the photon energy), $M = pB_o/B_e$, and I_n is the nth modified Bessel function of the first kind. We use (3) to determine the probability distribution functions for the ONEs and the ZEROs, accounting for the finite extinction ratio via $E_{\rm ZERO} = \varepsilon E_{\rm ONE}$. We then determine $P(1|0)$ and $P(0|1)$ for the optimum threshold via numerical integration and calculate the BER via $(P(1|0)+P(0|1))/2$.

As an example, consider an $R = 10.7$ Gb/s NRZ OOK preamplified receiver with a gain of 30 dB and a noise figure of 3.4 dB $(n_{\rm sp} = 1.1)$. Selecting an approximately optimal combination [16] of $0.7R = 7.5$ GHz electrical filter and $1.7R = 18.2$ GHz optical filter as the reference and assuming $\eta_{\rm in} = 0.95$, $p = 2$, and $Q = 6$ $({\rm BER} = 10^{-9})$ results in the families of receiver sensitivity curves shown in Fig. 1. As has been noted [11], [15], the Gaussian approximation is significantly conservative in predicting the attainable sensitivity. With a 30-dB extinction ratio, the penalty for an 800-GHz filter is 3.4 dB for the Gaussian approximation and 4.2 dB for the chi square statistics. The results show that the penalty due to a finite extinction ratio is also significant; with an 18.2-GHz optical filter, the penalty for a 10- versus 30-dB extinction ratio is ~2.8 dB for both Gaussian and chi square statistics. For these assumptions and a 33-GHz carrier spacing, the worst degradation in receiver sensitivity predicted by the chi square model for a given extinction ratio is 1.7, 2.5, and 3.5 dB for filters supporting 4, 8, and 16 wavelengths, respectively, which occurs for 30-dB extinction.

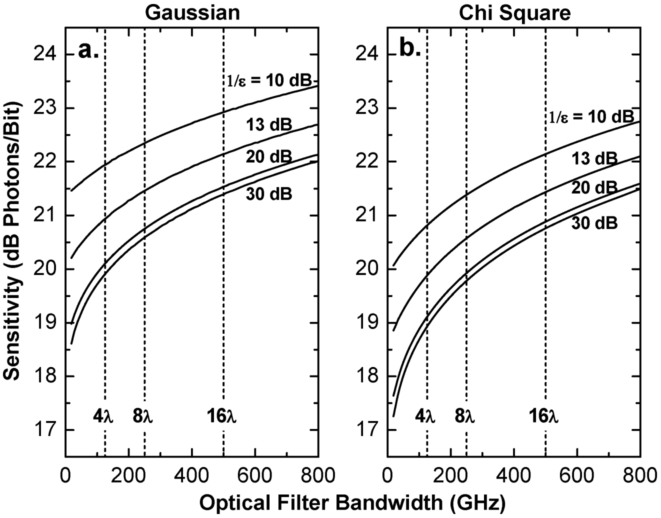

Fig. 1. Receiver sensitivity at BER $= 10^{-9}$ as a function of optical filter bandwidth for various extinction ratios and $p = 2$ using (a) Gaussian statistics, and (b) chi square statistics. Dashed lines indicate the filter bandwidth needed for four, eight, and sixteen wavelengths at 10.7 Gb/s with a spacing of 33 GHz.

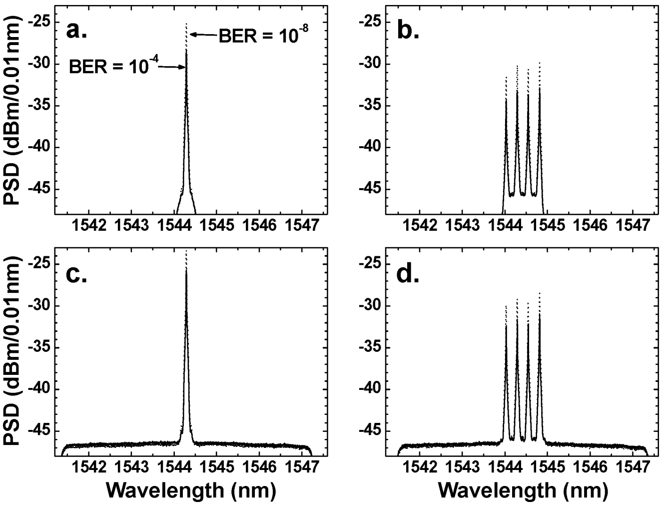

Fig. 2. Measured power spectra for BER $= 10^{-4}$ (solid line) and 10^{-8} (dashed line) with (a) one wavelength and $B_o = 63$ GHz, (b) four wavelengths and $B_o = 125$ GHz, (c) one wavelength and $B_o = 750$ GHz, and (d) four wavelengths and $B_o = 750$ GHz.

III. EXPERIMENT

We investigate the filter penalty with a multiwavelength experiment. Our transmitter consists of four tunable external cavity lasers combined with a passive coupler, modulated with a 10.7-Gb/s NRZ $2^7 - 1$ pseudorandom pattern via an electrooptic Mach-Zehnder modulator, and amplified with an erbium-doped fiber amplifier (EDFA). A variable optical attenuator (VOA) is used to control the power into the receiver, which consists of a low-noise EDFA followed by a variable bandwidth tunable optical filter, a 10-GHz pin photodetector, and an electrical filter with a measured response that is well approximated by a fifth-order Bessel function with a 7.8-GHz 3-dB frequency. The VOA was used to set the SNR to achieve a particular BER (either 10^{-4} or 10^{-8}), and was then adjusted to maintain the same BER while the optical filter bandwidth was varied. Data were collected with a single wavelength and with four approximately equal-power wavelengths spaced by three times the data rate (~33 GHz) to eliminate beating effects. Power spectra of the cases corresponding to the minimum and maximum optical filter bandwidth are shown in Fig. 2, where 125 GHz is the minimum bandwidth that allows transmission of the four signal wavelengths without significant clipping.

The measured sensitivity results are shown in Fig. 3. Theoretical predictions using (1) and (3) are also shown, using parameters corresponding to the experimental conditions: $G = 43.2$ dB, $n_{\rm sp} = 1.1348$, $B_e = 7.8$ GHz/0.96 [16], $\eta_{\rm in} = 0.98$,

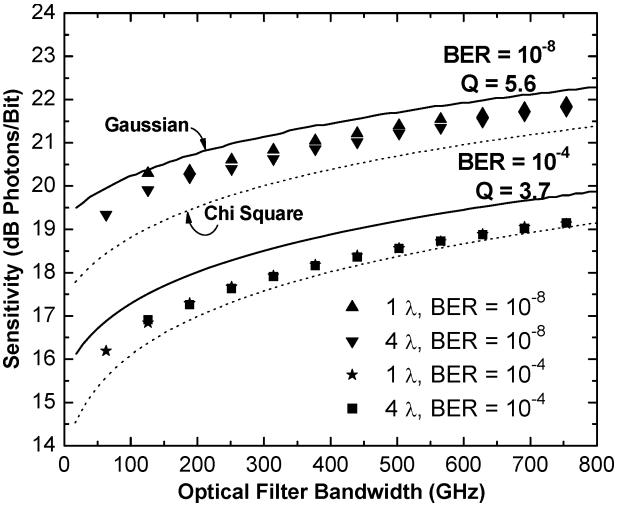

Fig. 3. Measured and predicted receiver sensitivity as a function of optical filter bandwidth for BER $= 10^{-4}$ and 10^{-8}. Gaussian: solid line; chi square: dashed line.

$p = 2$, and $\varepsilon = 0.0325$. The agreement between data and theory is excellent, and shows that the power penalty due to suboptimal filtering is <4.6 dB at a BER of 10^{-4} for a filter bandwidth up to 800 GHz. The remainder of the penalty relative to ideal preamplified OOK is dominated by the 14.9-dB extinction ratio of our modulator. At a BER of 10^{-8}, the penalty due to suboptimal filtering is <3.6 dB for filters up to 800 GHz. The agreement between single- and multiwavelength data is also excellent, confirming the absence of beating effects.We note that the penalty due to excess ASE could be reduced using a periodic filter such as a Mach–Zehnder interferometer with transmission peaks matched to the center wavelengths of the lasers. Also, polarization interleaving of the wavelengths would enable the carrier spacing and optical filter bandwidth to be reduced by a factor of two.

IV. CONCLUSION

The spatial diversity technique for fade mitigation necessitates a wide optical filter in the receiver, causing a power penalty relative to the single-wavelength case with optimal filtering. We have quantified the variation in receiver sensitivity caused by a wide optical filter in an optically preamplified receiver where the noise is dominated by the signal × ASE and ASE × ASE terms. The theoretical results compare favorably with experimental results in both single-wavelength and multiwavelength configurations. For a four-wavelength, 10.7-Gb/s, NRZ OOK preamplified system without a polarization filter, the penalty is found to be <4.6 dB at BER $= 10^{-4}$ for a filter as wide as 800 GHz. With reasonable components, a sixteen-wavelength system could be implemented with <3.5-dB penalty at BER $= 10^{-9}$. The penalty can be reduced by using a periodic filter and/or polarization interleaving.

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