The Use of an Optical Fiber Amplifier in the Reference Arm of a Wavefront Sensing Interferometer

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Abstract: When a fiber amplifier is part of an optical wavefront sensor, design constraints are different than in standard applications. We illustrate amplifier optimizations (for this regime) facilitated by novel closed-form solutions for gain and noise.

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1. Introduction

Self-referencing interferometers are often used as wavefront sensors in systems with adaptive optics (AO) correction for applications in high scintillation environments [1], [2]. By incorporating a variable gain amplifier in the sensor, as in figure 1, it is hoped that performance can improved by optimizing the gain to initiate the closing of the AO loop (during the acquisition of lock) and then increase the gain during the closed-loop tracking of the signal. Another reason for putting a fiber amplifier in one arm of the interferometer is that the single-mode fiber creates a spatio-temporal filter and without significantly attenuating the signal beam we can create a clean local-oscillator so that we can more selectively extract the phase information of the wavefront after atmospheric scattering (or scattering off of other targets). By varying the angle of incidence into the single-mode fiber we can select the spatio-temporal part of the scattered beam that we with to focus on – thereby sorting out the available phase information in novel ways. By turning the fiber into a fiber amplifier we avoid having to attenuate an already significantly attenuated scatterer. The amplifier also automatically provides an external gain control for the detector (via the fiber's pump power) which is useful in a variety of real-world sensing scenarios (e.g., in addition to AO lock acquisition vs tracking issues, one might need to respond to a cooperative high-signal beacon to prevent CCD saturation).

To properly asses the potential performance advantages of such a scheme one must carefully take into account the fact that *any* amplifier introduces its own internal noise (in addition to amplifying the signal and noise at its input port). Due to the nature of the signals involved in the sensor application however, one cannot simply characterize the amplifier noise via a single number (such as noise figure, as one might be tempted to use in the more standard telecommunications applications). Moreover, the telecommunications "rules of thumb" involve assumptions based on relatively high input signal intensities and moderate gain levels (so that the signal-spontaneous beat noise [3] is dominant, etc.). These are certainly not applicable to the sensor signal environment (with low input intensities of perhaps -40dBm, or even -70dBm, in contrast to over +20dBm as found in most telecommunication applications). At these low input signal intensities the amplified spontaneous emission (ASE) shot noise and (depending on the gain) the ASE-ASE beat noise turn out to be dominant – whereas both of these terms are assumed to be negligible in telecommunications. Also, rather than assuming a perfect population inversion we incorporate more realistic models of pumping (as we must, since we wish to vary the gain). Moreover, we find that when we also include the spatial variation of this inversion (due to pump depletion) that for: a given input intensity and a given desired gain; the minimization of the noise involves an optimization over a class of two functions (not just a single number) as will be demonstrated in section 3. Even in the telecommunications (sig-sp beat dominant) limit there is considerable debate as to the relevance of attempting to utilize optical noise figures [4], [5]. Thus, we will focus instead on actual noise power levels throughout the remainder of this paper.

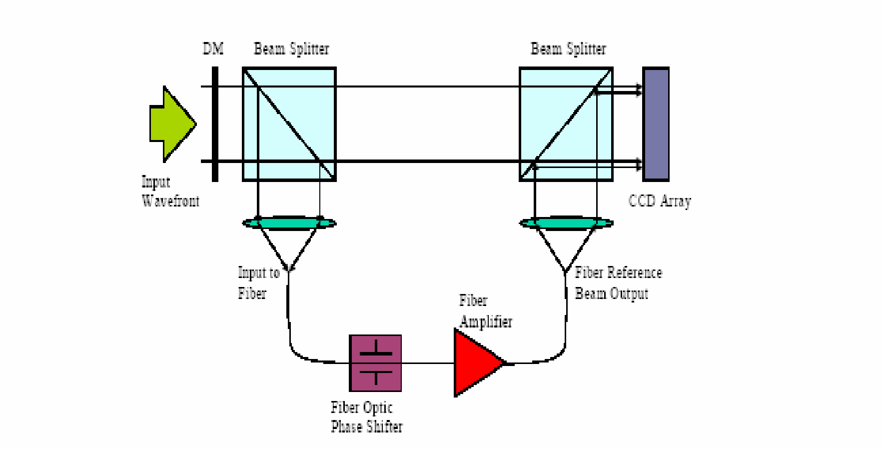

Fig. 1 Wavefront Detector with Fiber Amplifier

2. Models of Optical Fiber Amplifier Noise

Since the novelty of our application will take us into a realm where an inconsistency arises between the quantum and semiclassical models of beat noise, it is important that we take a little time to carefully review these models. The standard quantum treatment of optical fiber amplifier noise is a single-mode theory, i.e., only one frequency mode of the electromagnetic field (the signal) is treated as a quantum field. The ASE field arises only via the spontaneous and stimulated transitions of the quantum two-level atomic system to which the quantum (signal) field is coupled. Since the ASE modes themselves are not directly treated as quantum fields it is suspected that this standard quantum model can not *completely* describe the spectral aspects of beat noise processes [6].

By considering electric dipole transitions into and out of the photon number states of the signal field, one obtains rate equations for the evolution of the photon number statistics as the field propagates along the fiber to some distance, z. Neglecting saturation of the atomic levels and other nonlinearities, the solution of these rate equations yields the variance of photon number. In addition to the "excess noise" (which vanishes for the case of an input signal field with Poissonian number statistics) the quantum theory yields four terms: the signal shot noise; the ASE shot noise; the signal-spontaneous beat noise; and the ASE-ASE beat noise. Those last four terms (shown in figure 2) have their counterpart in the other model.

$$\sigma_n^2 = G^2(z)\left[\sigma_0^2 - \langle\hat{n}(0)\rangle\right] + G(z)\langle\hat{n}(0)\rangle + N(z) + 2G(z)\langle\hat{n}(0)\rangle N(z) + N^2(z)$$

is the variance of the photon number (# of clicks per integration time)

$$G(z) \equiv \exp\left\{\int_0^z [a(\zeta) - b(\zeta)]\,d\zeta\right\}$$

is the gain of the amplifier and

$$N(z) \equiv G(z)\int_0^z a(\zeta)/G(\zeta)d\zeta$$

is the ASE noise.

Fig. 2 Quantum Model (variance of photon number)

$$P^e_{sig} = (2eB_e)(\frac{e}{\hbar\omega})[GP_s^{in}]$$

$$P^e_{ASE} = (2eB_e)(\frac{e}{\hbar\omega})[B_o\hbar\omega n_{sp}(G-1)]$$

$$P^e_{sig-sp} = (2eB_e)(\frac{e}{\hbar\omega})[GP_s^{in}n_{sp}(G-1)] \quad \text{and}$$

$$P^e_{ASE-ASE} = (2eB_e)(\frac{e}{\hbar\omega})[B_o\hbar\omega\{n_{sp}(G-1)\}^2].$$

Fig. 3 Semiclassical Model (electrical noise)

In the semiclassical model of amplifier noise however, we treat all fields as classical waves and *assume* a uniform spectral density of ASE noise. This model then obtains four noise currents from the squaring of the incident signal and ASE field amplitudes. These four noise currents are analogous to the last four terms of the photon number variance (the semiclassical model doesn't produce the first term, hence the phrase "excess noise").

Whether we use the quantum or the semiclassical, a.k.a. "electrical," model is irrelevant as long as they simply map to each other via a constant. Noting that N = (G-1) Nsp, we find that when the electrical bandwidth, Be, is small compared to the optical bandwidth, Bo, such a mapping is always possible. When we don't have the condition Be << Bo however, we find that a discrepancy unavoidably exists between the quantum and semiclassical models in their prediction of the ASE-ASE beat noise. In telecommunication applications this noise is minimal and is typically entirely dismissed. In low input signal applications however (such as sensors, etc.) the ASE-ASE beat noise often turns out to be the dominant term. This is far more than just an academic issue for low input signal applications also because to reduce the dominant (ASE-ASE) noise we often wish to reduce the optical bandwidth as much as possible (thereby bringing us into the realm where the discrepancy exists). For more on the spectral aspects of the beat noise one is directed to [6] and [7]. In the remainder of this paper we will remove this issue by assuming Be << Bo. Also, although a severely attenuated laser beam has Bose-Einstein rather than Poissonian statistics, this discrepancy diminishes under this condition (Be << Bo) thereby diminishing the "excess noise" term.

3. Closed-form Tools for Optimizations in the Presence of Pump Depletion

We also consider the effects of pump depletion and find that we can obtain novel closed-form solutions, which facilitate the optimization of the performance of optical fiber amplifiers. The extent of our numerous findings will be presented elsewhere but the AO community needs to be made aware that it is now possible to perform such optimizations (via the use of Mathematica) and that in our sensor regime, the conventional amplifier wisdom is no longer applicable. In standard applications, for example, the gain and noise are similar curves along the distance z down the fiber so that Nsp = N(z) / [G(z) -1], is approximately a single number that can characterize the amplifier's noise figure. In our applications however, this is typically not the case. In low input signal applications, for example, the ASE-ASE beat noise (proportional to the square of the gain) often dominates, and so one prefers to operate at lower gain. At lower gain however, N(z) and G(z) are less similar, as demonstrated in figure 4, so that Nsp is not a constant, as demonstrated in figure 5, where No is proportional to the pump power (and hence also the peak gain).

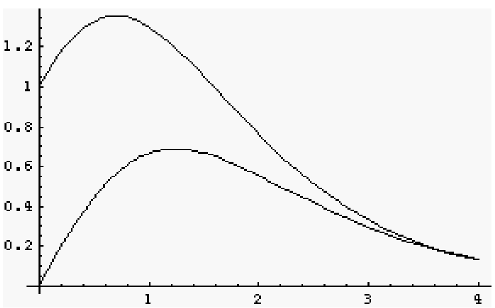

Fig. 4 G(z) [top] and N(z) for No=1

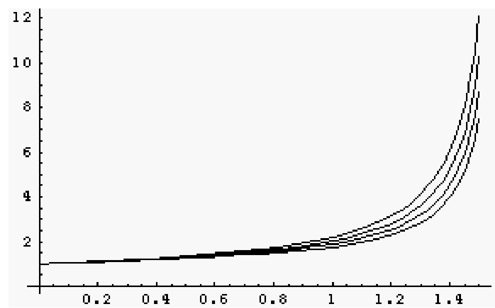

Fig. 5 Nsp for No=1 [bottom] to No=4 [top]

Since in our sensor applications regime the gain and noise don't peak at the same location, in order to achieve a specific gain and minimize noise it is sometimes preferable to pump harder rather than operate at the gain peak. Thus, for wavefront sensor applications the minimization of the noise (for fixed input signal intensity and fixed amplifier gain) really involves an optimization over a class of two functions (not just a single number). Numerous specific optimization results will be illustrated in the presentation.

4. References

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