Gain spectrum of an optical parametric amplifier with a temporally-incoherent pump.

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Abstract: We report on the performance of a fiber optical parametric amplifier pumped with a temporally-incoherent pump. Parametric gain coefficients seven times higher than that of a coherently pumped amplifier are demonstrated.

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1. Introduction

The properties of fiber optical parametric amplifiers have been the subject of extensive study with many applications proposed including optical amplification, wavelength conversion, and nonlinear optical signal processing [1]. Whilst in the standard analysis the pump is considered to possess perfect temporal coherence, recent work has investigated the effects of using a temporally-incoherent wave as the parametric pump [2,3]. In this paper we consider the specific case of the amplification of a coherent signal by an incoherent pump. One of the consequences of using an incoherent pump is that the intensity and phase fluctuations of the pump are transferred to the initially coherent signal. Thus a disadvantage of incoherent pumping is that considerable noise is added to the amplified signal. However, depending on the application, this can be offset by the key advantage of incoherent pumping: that an incoherently pumped parametric amplifier can exhibit considerably more gain than a coherently pumped amplifier operating at the same power level. We restrict our attention to the regime in which the length of the fiber is much smaller the dispersion length, and the bandwidth of the pump is small enough to avoid dephasing the parametric amplification over the length of the amplifier. Under these conditions we are able to derive a simple result for the optimum incoherent parametric gain experienced by the signal. For the parameters considered in this paper an incoherent amplifier is shown to have a parametric gain coefficient seven times higher than that of an equivalent coherently pumped parametric amplifier. We then present measurements of the gain of an incoherently pumped parametric amplifier as a function of pump power and detuning. To our knowledge this is the first time such measurements are presented. Applications of incoherently pumped parametric amplifiers could be envisioned in the fields of optical band conversion [4] and $\chi^{(3)}$ optical parametric oscillators [5], both of which would benefit from the increased parametric gain available from incoherently pumping.

2. Theory

We consider a partially incoherent pump source derived from a polarized, spectrally-filtered, ASE source (3 dB spectral width $d\Omega$). This sets the coherence time of the source as, $t_{coh} \approx 2\pi / d\Omega$, and the statistics of the pump power as that of a polarized thermal source [6]:

$$p(P) = \frac{1}{\langle P \rangle} e^{-\frac{P}{\langle P \rangle}} \tag{1}$$

where $p(P)$ is the probability distribution of the instantaneous pump power P. To proceed we assume the length of the amplifier is much less than the dispersion length $L_D = t_{coh}^2 / |\beta_2|$, and the dephasing of the parametric gain due to the finite bandwidth of the pump is small ($\Delta k_{d\Omega} L \ll \pi$). Under these conditions we can approximate the mean parametric gain of the coherent seed as:

$$G_{\text{mean}} = \int_0^\infty p(P) G(P) dP \tag{2}$$

where $G(P)$ is the signal gain of a parametric amplifier pumped with a CW coherent pump (power P). This gain calculation must include the effect of pump depletion or the integral will not converge. To do this $G(P)$ is calculated numerically from the full four-wave-mixing coupled mode equations of Ref. [7]. From here it is possible to evaluate Eqn. (2) to calculate the mean parametric gain of a coherent signal in a parametric amplifier pumped by an incoherent pump. We note that the gain calculated from Eqn. (2) is the optimum incoherent gain attainable. Any evolution (other than depletion) in the pump's temporal profile, or dephasing of the parametric process due to the pump's finite spectral width, will result in a reduction in the observed gain.

The amplifier we wish to consider in the experimental section that follows has the following parameters: $L = 100$ m, $\gamma = 0.0253$ W^{-1}km^{-1}, $\langle P \rangle = 4$ W and $P_{signal} = 0.1$ µW. The dispersion parameters of the fiber measured at 1555 nm are $\beta_2 = -0.10$ ps^2/km, and $\beta_4 = -7.1\times10^{-4}$ ps^4/km. For these parameters we calculate the mean parametric gain of the incoherently pumped amplifier via Eqn. (2). In Figure 1 we plot this curve as a function of average pump power (solid line), also plotted in Fig. (1) is the equivalent curve for a coherently pumped parametric amplifier. At low powers the incoherently pumped amplifier has a parametric gain-slope of 15.4 dB/W, seven times higher than that of the coherently pumped amplifier. Above 5 W average pump power the incoherent gain starts to strongly saturate due to the effect of pump depletion.

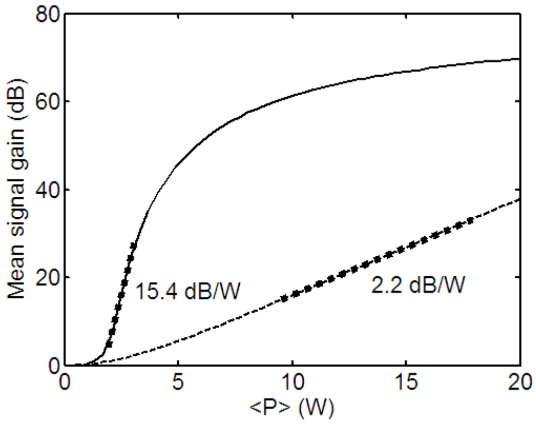

Fig. 1. Mean parametric gain of a coherent signal as a function of pump power for an incoherently pumped amplifier (solid line) and a coherently pumped amplifier (dashed line).

3. Experiment

To experimentally generate an incoherent pump wave we follow the experimental scheme proposed in Ref. [3]. A 500mW C-band ASE source is filtered by a 0.1 nm spectral filter centered at 1555 nm. This filtered signal is then polarized and intensity modulated with 10 ns pulses with a duty cycle of 33%. This modulation reduces the average power of the input signal and prevents saturation of the Erbium amplifiers which follow. The incoherent signal is then amplified first by a high-gain Erbium amplifier (EDFA 1), then by a second booster amplifier (EDFA 2). After each amplifer the signal is filtered by a 1 nm bandpass filter to remove unwanted ASE. A schematic diagram of the setup is shown in Fig. 2.

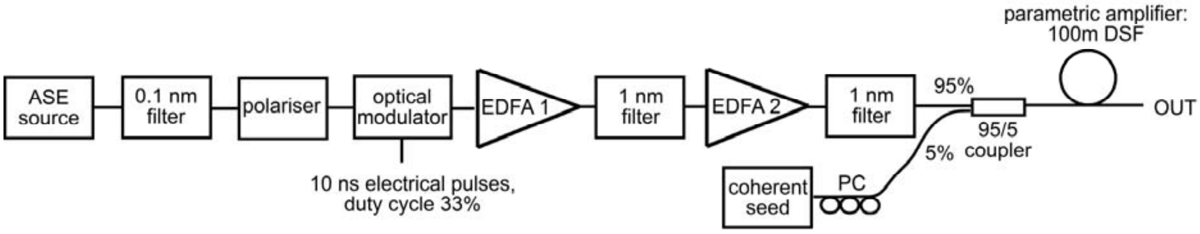

Fig. 2. Schematic diagram of the incoherently pumped optical parametric amplifier.

The parametric amplifier consists of 100 m of standard telecommunications dispersion shifted fiber (DSF) whose parameters were given in the preceding section. The first experimental measurement we present is the parametric gain spectrum of the amplifier at an average incoherent pump power of 4 W. The power level of the input seed was 0.1 μW injected on the high-frequency (anti-Stokes) side of the pump. The experimentally measured gains are plotted in Fig. 3(a) as solid circles. The solid line is the theoretical prediction of the incoherent gain theory presented above, the dashed line the predicted gain curve for a coherently pumped amplifier at the same power. The experimentally measured points are ~ 5 dB below the predicted incoherent gain. This difference is expected as theoretical curve does not account for the dephasing of the parametric pump due to the finite bandwidth of the pump. Also as the signal is injected on the anti-Stokes side of the pump it experiences an additional loss due to stimulated Raman scattering from the signal into the pump.

Next we measure the coherent and incoherent gain of the amplifier as a function of pump power. At each power the detuning of the seed is scanned to find the maximum gain and the measurement is made at this point. Again the coherent seed power level is 0.1 μW injected on the anti-Stokes side of the pump. The measurements are plotted in Fig. 3(b), the experimentally measured gains of the incoherent amplifier are shown as solid circles, the measured gains of the coherent amplifier are shown as open circles. To obtain sufficient pump power to make the coherent gain measurements it was necessary to lower the duty cycle of the modulator to 10 %. The solid line in Fig. 3(b) is the theoretical prediction of the incoherent gain theory presented above, the dashed line the predicted gain curve for a coherently pumped amplifier. Again both sets of experimental curves lie slightly under the theoretical predictions for the reasons discussed above. The incoherent gain curve has a maximum measured parametric gain-slope of 14.3 dB/W at a pump power of 2.5 W. This is seven times higher than the experimentally measured coherent gain-slope of 1.9 dB/W, clearly demonstrating the increased gain possible with an incoherently pumped parametric amplifier. In conclusion we have presented, what to our knowledge, are the first detailed measurements of the gain spectrum of a fiber optical parametric amplifier operating with a temporally-incoherent pump. Applications which require high parametric gain, but not necessarily high signal fidelity, could benefit from the use of an incoherently pumped parametric amplifier.

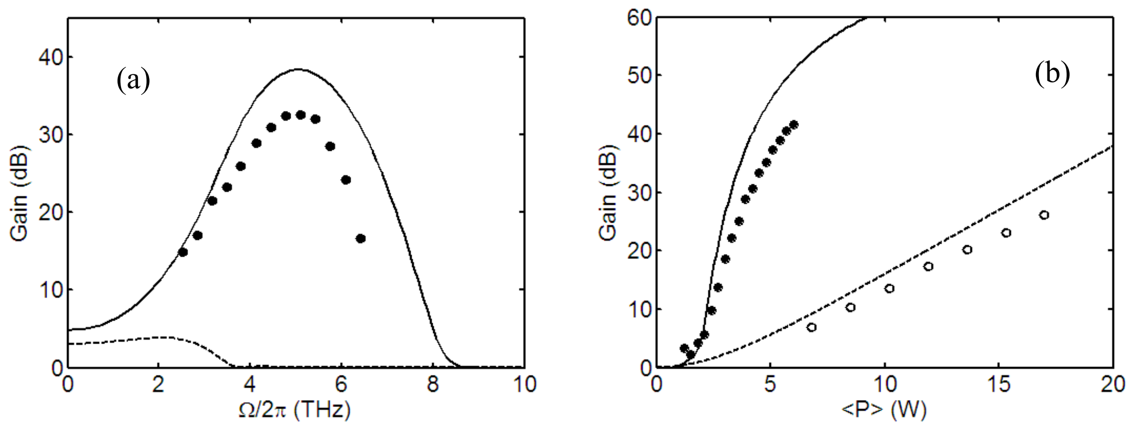

Fig. 3. (a) Measured incoherent parametric gain as a function of (positive) seed detuning at an average pump power of 4 W (solid circles). The solid line is the predicted incoherent gain, the dashed line the predicted coherent gain at the same pump power. (b) Measured incoherent (solid circles), and coherent (open circles), parametric gain as a function of pump power. The solid line is the predicted optimum incoherent gain, the dashed line the predicted coherent gain.

4. References

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