Parametric Amplification and cascaded FWM in Optical Fibers

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Abstract

Four wave mixing in optical fibres and other waveguide structures has been studied for several decades since low attenuation optical fibres were first manufactured. The process is responsible for a variety of nonlinear optical phenomena including Modulation Instability, Phase Conjugation (or two pump parametric amplification) and Bragg Scattering (or wavelength exchange). Four wave mixing can be utilised to generate optical gain via parametric amplification using either one or two pumps, and such parametric amplifiers have the potential to compete with other optical amplifers which are currently in use commercially. Unlike the amplifiers based on fiber Raman gain or rare earth doped fibres, the parametric amplifier is inherently a phase sensitive amplifier. It also has the advantage, in common with the Raman amplifier that it can potentially operate at any wavelength. The major limitations on the operation of the amplifier are the availability of suitable pumps and the uniformity of the optical fibre.

Groups in different laboratories have recently demonstrated significant improvements in the operation of fiber optical parametric amplifiers and oscillators, using novel pump sources and fibers. The main fiber advances which have contributed to this performance improvement are the availability of photonic crystal fibers (PCF) which have led to optical parametric amplifiers and oscillators in the visible, and highly nonlinear fibers (HNLF) which have contributed to improved performance in the infra red. It has also become apparent in both HNLF and PCF based amplifiers that the major limitation to the performance is now the uniformity of the fiber itself. Whilst in principle these amplifiers could be further improved, this would require very strict limits to be placed on the diameter fluctuations of the fiber itself[1].

Optimising the design a single pump oscillator in our laboratories has led to the demonstration of a multi Watt level tuneable optical fiber parametric oscillator with a tuning range in excess of 500nm (70THz) in the infra red using a HNLF. A tuning range of 180nm (160THz) has also been demonstrated in the visible using a PCF.

The nonlinear interaction of two pumps, separated by a frequency $\mathbf{\Delta}$, propagating in an optical fiber, generates two sidebands themselves detuned from the two pumps by $\mathbf{\Delta}$. At sufficiently high power this process can continue as a cascade with the *nth* sideband detuned by $(n+0.5)\Delta$ from the center frequency. Strong amplification of the *nth* sideband is possible provided that the sum of the wavevector mismatches of the *n* elementary FWM processes required to generate the *nth* sideband is zero [2]. This has recently been demonstrated experimentally for cascades designed to phase match high order (the n = +6 and n = -4) sidebands. It has been found that the phase-matched frequency shift of the *nth* sideband corresponds exactly to the frequency shift of a dispersive wave emitted by a soliton centered at the center frequency of the two pumps [3]. A careful analysis of this process has enabled cascaded FWM to be identified as the nonlinear mechanism that drives dispersive wave emission.

In addition, this frequency domain theory also predicts that a pump propagating in the normal dispersion regime can emit a dispersive wave in a manner entirely analogous to the emission of a dispersive wave by a soliton [4]. Other experiments have unequivocally demonstrated this emission and a similar process involving cascaded nonlinear Bragg scattering. This cascaded theory will play an important role in the future development of optical frequency combs in both optical fibers and high-Q micro-resonators.

References

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