OPTICAL COMMUNICATIONS

Amplifying to perfection

The demonstration of a phase-sensitive optical amplifier with a noise figure of just 1.1 dB — three times lower than that of a conventional amplifier — could help significantly extend the reach of optical communications systems.

Guifang Li

Following its invention in the late 1980s, the erbium-doped fibre amplifier (EDFA) rapidly evolved to become a key device for long-haul fibre-optic communication. Its ability to boost signals in the optical domain and thus compensate for transmission losses without needing to convert signals back to the electrical domain transformed ultralong submarine links at the turn of the twenty-first century.

Although amplifiers play a crucial role in boosting the strength of a signal, they also amplify any noise present at the input and add noise to the output. As a result, the output signal-to-noise ratio (SNR) after an amplifier is always lower than, or at best equal to, the SNR at the amplifier input. The ratio of the input SNR to the output SNR is known as the amplifier's noise figure. An ideal amplifier that does not produce excess noise has a noise figure of one. For a high-gain EDFA, the theoretical limit of the noise figure is two (3 dB). This limit is fundamental to all forms of phase-insensitive amplifiers (PIAs), including Raman amplifiers and EDFAs.

Now, writing in *Nature Photonics*, Tong and co-workers report near-perfect optical amplification with a noise figure of just 1.29 (1.1 dB; ref. 1) — the lowest achieved to date and well beyond the capabilities of EDFAs or Raman amplifiers. Their experiment is schematically summarized in Fig. 1.

The noise properties of an amplifier depend on the number of modes participating in the amplification process[2]. In materials that exhibit third-order optical nonlinearity such as optical fibres, signals can be amplified through the four-wave mixing parametric process, in which two pump photons at frequencies of ω_{p1} and ω_{p2} are converted into signal and idler photons at frequencies of ω_s and ω_i, respectively. Energy conservation requires that $\omega_{p1} + \omega_{p2} = \omega_s + \omega_i$. In the 'degenerate' situation for four-wave mixing, where the output frequencies of the signal and idler are equal ($\omega_s = \omega_i = (\omega_{p1} + \omega_{p2})/2$), the amplification is phase-sensitive. In particular, an in-phase signal with phase θ_{i0} will be amplified while a quadrature signal with phase $\theta_{i0} + \pi/2$ will be attenuated.

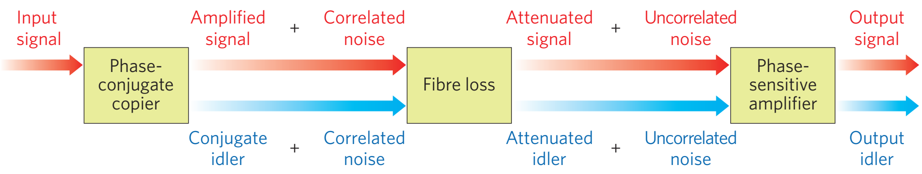

Figure 1 | Schematic of the copier, loss and PSA stages in the work of Tong *et al.*, indicating the evolution of the signal, idler and noise along the link.

There is only one mode participating in the degenerate phase-sensitive amplification process of the in-phase signal. As a result, the phase-sensitive amplifier (PSA) is ideal and has a theoretical noise figure limit of one (0 dB).

Although the noise performance of a PSA is a highly attractive prospect, achieving phase-sensitive gain is generally inconvenient: not only does it need the signal to be confined in one specific phase for amplification[3] and regeneration[4], but it also requires the pump and signal to be phase-coherent. However, the results provided by the non-degenerate PSA ($\omega_s \neq \omega_i$) of Tong *et al.* suggest that the rewards are worth the trouble. Their amplifier offers a low noise figure of 1.1 dB while providing a gain of 26.5 dB, which is suitably high for practical applications.

As shown in Fig. 1, prior to entering the PSA, the input signal is first passed through a phase-conjugate copier comprised of a pump and a highly nonlinear fibre, which together generate a phase-conjugate idler at a different wavelength. At this point, the noises of the signal and idler are correlated. After fibre attenuation, the signal and phase-conjugate idler remain correlated, while the noises become uncorrelated. The PSA, which also consists of a pump and a highly nonlinear fibre but with inputs at both the signal and idler wavelength, amplifies the incoming signal and idler in a phase-sensitive manner.

The non-degenerate PSA of Tong *et al.* provides a fourfold improvement in phase-sensitive amplification over a PIA, owing to the correlation between the input and idler signals. In the scenario of completely uncorrelated input and idler noise, the output noise of the non-degenerate PSA matches that of a PIA[5,6].

This information might suggest that the noise figure of the non-degenerate PSA is four times (6 dB) that of the non-degenerate PIA. However, this is not quite correct as the signal and idler both carry the same information and the aforementioned fourfold increase in phase-sensitive amplification can only be accomplished when both signals are present. The input SNR is effectively two times the input signal SNR; thus, the noise figure of the non-degenerate PSA is two times (3 dB) better than the non-degenerate PIA and the same as a degenerate PSA.

The fact that the PSA of Tong *et al.* is non-degenerate brings with it benefits that come at the cost of additional complexity. One advantage is that the system becomes compatible with large amplification bandwidths and multiple-wavelength channels. In contrast, a degenerate PSA only operates at a single frequency. A non-degenerate configuration has addition set-up complexities because the pump(s), signal and idler must all be phase-coherent. One method of phase-locking the signal and idler is to derive them from the same source. Double-sideband modulation of a pump produces phase-locked signal and idler signals with the same complex amplitude[7]. In addition, a non-degenerate PIA can be used to create a phase-locked idler from a signal and a pump[8].

Tong *et al.* point out that when the signal and idler are complex conjugates of each other at the input, the non-degenerate PSA can simultaneously provide phase-sensitive amplification to two orthogonal quadratures of the input. This is because equal in-phase components and opposite quadrature components for the signal and idler are simultaneously satisfied. The non-degenerate PSA with phase-conjugate inputs can therefore provide (pump) phase-sensitive gain for signals anywhere in the complex plane. Conveniently, the idler created by a non-degenerate PIA is an exact phase-conjugate copy of the signal.

Tong *et al.* demonstrate modulation-format-insensitive phase-sensitive amplification using a differential quadrature phase-shift keying signal and its complex-conjugate idler. They report that using the non-degenerate PSA as the pre-amplifier for the differential quadrature phase-shift keying receiver provides a 5.5 dB improvement in sensitivity over a PIA pre-amplifier.

Useful insight is also gained through an experimental comparison of the noise figures achieved by amplified fibre-optic transmission links that use either non-degenerate PSAs or PIAs (EDFAs)[3,8]. As long as the loss of the link is sufficiently high, the link noise figure will continue to be dominated by the noise associated with fibre loss, which not only makes noise generated in the PIA copier negligible, but also causes the noise in the signal and idler signals to be uncorrelated. Tong *et al.* report that their non-degenerate PSA achieves a link noise figure improvement of 5.2 dB over a PIA.

Although such improvements are indeed impressive, the complexity of the operating requirements may hinder practical implementations in the near future. In particular, the requirement that all the inputs must be phase-locked may prove to be a major obstacle for fibre-optic communication systems. Coherent receivers that derive data bits from the phase of a signal became practical only recently when hardware phase-locking was replaced by digital phase estimation. Moreover, for the non-degenerate PSA to operate properly, the signal and idler must be kept equal in power and remain phase-conjugates of each other at the input. PSAs are also usually polarization-sensitive; dynamic trimming of amplitude, phase and polarization is significantly more difficult than achieving phase-locking alone.

Future work must start by addressing these issues if PSAs are to be deployed in optical communication systems. The effects and practical performance limits due to spontaneous Raman scattering and pump noise transfer must also be investigated.

The improved link noise figure can be used to increase the data capacity of fibre-optic links, but the increase in capacity will be logarithmic with the received SNR. Because the non-degenerate PSA requires twice the bandwidth of a PIA or degenerate PSA, the capacity of links using non-degenerate PSAs may actually decrease if the corresponding EDFA/Raman systems already operate at high spectral efficiencies.

The alternative is to use the improved link noise figure to extend transmission distances. It is known that links with distributed amplification perform better than those with discrete 'lumped' amplifiers. It would be interesting to explore the possibility of achieving even lower link noise figures using distributed non-degenerate PSAs with phase-conjugate inputs[6]. Finally, many long-haul fibre-optic transmission systems are migrating to digital coherent detection, in which there is no optical dispersion compensation. This makes phase trimming of the signal and idler very difficult and may prevent the use of non-degenerate PSAs in such systems. ❐

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References

1. Tong, Z. *et al. Nature Photon.* **5,** 430–436 (2011).
2. McKinstrie, C. J., Yu, M., Raymer, M. G. & Radic, S. *Opt. Express* **13,** 4986–5012 (2005).
3. Marhic, M. E., Hsia, C. H. & Jeong, J. M. *Electron. Lett.* **27,** 210–211 (1991).
4. Croussore, K. & Li, G. *IEEE Photon. Technol. Lett.* **19,** 864–866 (2007).
5. McKinstrie, C. J. & Radic, S. *Opt. Express* **20,** 4973–4979 (2004).
6. Vasilyev, M. V. *Opt. Express* **13,** 7563–7571 (2005).
7. Tang, R., Devgan, P., Grigoryan, V. S. & Kumar, P. *Electron. Lett.* **41,** 1072–1074 (2005).
8. Tang, R., Devgan, P. S., Grigoryan, V. S., Kumar, P. & Vasilyev, M. *Opt. Express* **16,** 9046–9053 (2008).

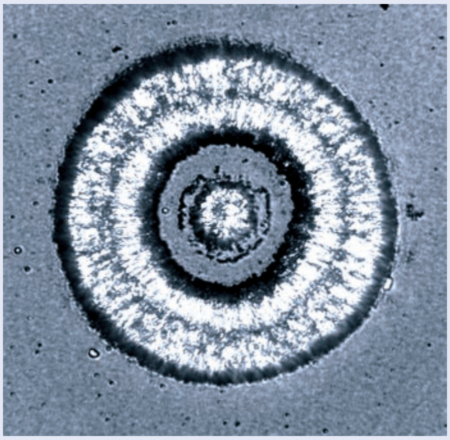
IMAGING

Shocking observation

Using intense laser pulses to generate strong shock waves is a well-known technique for compressing fuel pellets in laser fusion and strengthening critical metallic components such as turbine blades in jet engines. Unfortunately, however, visual observation of this process is not straightforward.

Scientists from the USA and France have now developed an ultrafast imaging technique that allows direct real-time observation of the generation, propagation and focusing of laser-driven shock waves in water (*Phys. Rev. Lett.* **106,** 214503; 2011).

Single-shot acquisitions collected by a camera revealed that such shock waves can reach supersonic speeds of Mach 6 (~2 km s^{-1}), which corresponds to a pressure of around 30 GPa at the shock focus.



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The researchers used an axicon conical prism and a lens to focus laser pulses of several millijoules (800 nm in wavelength and 300 ps in duration) to a 10-μm-wide, 200-μm-diameter ring in a 5-μm-thick water solution containing a 2 wt% suspension of carbon nanoparticles.

The incident light vaporized the nanoparticles and hence generated a shock wave. The researchers sent weak probe light pulses through the sample for collection at a CCD camera, which made it possible to record either two-dimensional spatial images, streak images using one axis of the detector as time, or interferometric images using a set of reference pulses. Features such as the shock focus and cavitation were clearly observable in the streak images.

The researchers say that they will now study shock waves in solid samples, as well as chemical and structural transformations at the shock focus.

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