FIBRE COMMUNICATIONS

Time-reversed twin

Co-propagating a signal with its phase conjugate along an optical fibre link makes it possible to mitigate unwanted nonlinear distortions and improve the signal-to-noise ratio in long-haul optical communication systems.

Ezra Ip and Joseph M. Kahn

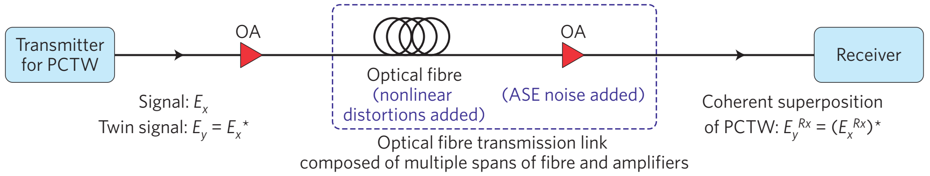

Figure 1 | Schematic of the PCTW scheme. A signal E_x and its phase-conjugate twin $E_y = E_x^*$ are transmitted on the two orthogonal polarizations of an optical carrier. Transmission through optical fibres imparts both linear distortion (dispersion) and nonlinear distortion (the Kerr effect), and optical amplifiers (OAs) add amplified spontaneous emission (ASE) noise. At the receiver, coherent superposition of the received twin waves E_x^{Rx} and $(E_y^{Rx})^*$ substantially cancels the nonlinear distortion, increasing the effective signal-to-noise ratio. However, transmission of a signal and its phase-conjugate twin halves the number of data channels that can be transmitted on the link.

Optical fibres, although largely hidden from view, carry almost all the Internet's huge volume of data traffic. For over three decades, advances in underlying technologies (including the development of ultratransparent glass fibres and low-noise optical amplifiers) have enabled the data rates of fibre transmission systems to keep pace with the relentless traffic growth. However, a potential 'capacity crunch' is looming as traffic continues to grow at about 50% annually[1], whereas the maximum data rate of a fibre is approaching a channel capacity limit[2–5] dictated by information theory.

The channel capacity of an optical fibre is limited by amplifier noise. The effect of amplifier noise can be overcome by increasing the signal power, but only up to a limit imposed by the Kerr effect, an intensity-dependent change in the refractive index of glass. At sufficiently high signal powers, this optical nonlinearity causes signals and noise to mix as they propagate together over long distances[6], degrading the system's signal-to-noise ratio. Because of this nonlinearity, the capacity of a fibre increases with increasing launched signal power only up to an optimal power, above which the capacity is thought to decrease[3,4] (although a recent study[5] suggests that the capacity levels off rather than decreases).

As a result, much research has been dedicated to reducing the impact of nonlinearity in a fibre link, and various schemes for realizing this have been demonstrated. For example, mid-span phase conjugation[7] effectively 'time reverses' the signal channels halfway along the link. Another well-known and effective scheme is digital back-propagation[8], which employs electronic signal processing at the receiver to compensate for nonlinear impairments. However, all schemes developed to date have significant drawbacks, such as the additional cost and complexity associated with more signal processing, the need for extra hardware, greater bandwidth requirements and being ineffective in fibre links that do not have specific dispersion maps. These factors have thus far precluded the commercial deployment of any nonlinearity mitigation technique.

Now, writing in *Nature Photonics*, Xiang Liu and co-workers[9] report a transmitter-based technique that can be implemented with minimal additional hardware or signal processing. Their phase-conjugated twin-wave (PCTW) scheme involves transmitting a signal and its time-domain phase conjugate on orthogonal polarization states (Fig. 1). Because the two waves experience similar nonlinear effects during propagation, their nonlinear distortions are anticorrelated and can be cancelled by a receiver. Using a frequency-domain decomposition of the signal, Liu *et al.* showed that the nonlinearity can be cancelled with minimal algorithmic complexity when the fibre link has a symmetric dispersion map that satisfies $D(L - z) = D(z)$, where $D(z)$ is the accumulated dispersion at distance z and L is the total link length. Under this condition, the nonlinearity affecting one polarization of the PCTW signal is the time-domain phase conjugate of the other polarization and may be cancelled at the end of the link by using coherent detection and adding the two recovered signal polarizations. For an arbitrary fibre link, it is possible to guarantee the required symmetry of the dispersion map by precompensating half the link dispersion at the transmitter and post-compensating half the link dispersion at the receiver. The PCTW method can mitigate both intra- and interchannel nonlinearities.

An interesting result shown by Liu *et al.* is that PCTW transmission can be considered a form of nonlinear noise squeezing. Through a simple matrix transformation, the researchers showed that PCTW transmission is equivalent to transmitting two independent signals on two reference polarizations, with each signal being modulated along only one phase quadrature. The combined effect of signal propagation and PCTW detection is to force the nonlinear distortion onto the phase quadrature orthogonal to the signal modulation, so that the nonlinearity has little impact on signal detection.

In practice, PCTW is limited by amplifier noise and polarization-mode dispersion, so the 'conjugate-and-add' approach does not achieve perfect cancellation of nonlinearity. Performance degradation still occurs at high launch powers, but the partial cancellation increases the optimal launch power, permitting substantially improved signal quality and potentially longer or faster links. In one experiment reported by Liu *et al.*, the signal quality was improved by up to 7 dB relative to that for conventional polarization-multiplexed transmission. This observed improvement is larger than the 3-dB (twofold) diversity gain expected had there been no nonlinear cancellation effect.

The greatest advantage of the PCTW scheme is its simplicity. It can be implemented using commercially deployed coherent receivers, and requires only an additional conjugate-and-add operation per symbol prior to symbol detection. The only new hardware required is a digital transmitter capable of performing dispersion precompensation. Digital transmitters are under commercial development and are expected to be incorporated in next-generation transceivers to enable pulse shaping and digital precompensation of fibre impairments. Compared with digital back-propagation, which requires an order-of-magnitude higher algorithmic complexity than current 100-Gb s^{-1} receivers, the algorithmic complexity associated with PCTW is minimal.

PCTW transmission is not without some serious drawbacks, however. The most significant one is that the act of transmitting phase-conjugated signals on orthogonal polarizations halves the total number of data channels that can potentially be employed in a link, as it eliminates the possibility of polarization multiplexing the data. Depending on the baseline spectral efficiency of a link using standard polarization-multiplexed transmission, the PCTW scheme may in fact reduce the information capacity.

Consider a dispersion-uncompensated link whose nonlinear distortion is Gaussian distributed, thus allowing the channel capacity to be analysed using a generalized Gaussian noise model[10]. Without PCTW, the maximum achievable spectral efficiency is $C = N \times \log_2(1 + SNR)$ [b s^{-1} Hz^{-1}], where SNR is the effective signal-to-noise ratio and N is the number of dimensions ($N = 2$ for polarization-multiplexed transmission). Using PCTW, the maximum spectral efficiency is $C_{\mathrm{tw}} = (N/2) \times \log_2(1 + SNR_{\mathrm{tw}})$, where SNR_{tw} is the new effective SNR. At high baseline SNR values, the ratio of the spectral efficiencies $C_{\mathrm{tw}}/C \approx (SNR_{\mathrm{tw}}\ [\mathrm{dB}])/(2 \times SNR\ [\mathrm{dB}])$ is equal to half the ratio of the effective SNRs in decibel units. Consequently, unless SNR_{tw} [dB] is more than twice SNR [dB], the PCTW scheme will actually lower the spectral efficiency.

In one experiment conducted by Liu *et al.* over a link consisting of 40 × 80 km spans of standard single-mode fibre, an SNR improvement of 5.7 dB was observed, indicating that the PCTW scheme reduces the spectral efficiency unless the baseline SNR is less than about 5.7 dB. However, even if PCTW cannot increase the spectral efficiency to alleviate the 'capacity crunch', it may still be useful for increasing the system reach in links operating with low-baseline SNRs, which may be encountered in ultralong-haul transmission.

The final experiment conducted by Liu *et al.* focused on the system reach improvement offered by the PCTW scheme. The researchers reported transmission of a 400-Gb s^{-1} superchannel signal comprising eight 37.5-GHz-spaced wavelength channels, each modulated by 32-Gbaud quadrature phase shift keying over 160 × 80-km spans of True Wave Reduced Slope® fibre, which is particularly susceptible to nonlinear effects because of its low chromatic dispersion and small core area. The experiment achieved an excellent system reach, demonstrating the potential to enhance performance in ultralong-haul systems that use older fibres. ❐

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RAMAN SPECTROSCOPY

The effect of field gradient on SERS

Surface-enhanced Raman spectroscopy is normally associated with the enhanced electric fields that arise near metal nanoparticle surfaces. The contribution of field gradients has been unclear, but new research provides insights into their effect.

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Surface-enhanced Raman spectroscopy (SERS) is an important analytical tool because it has low detection limits and can provide molecular fingerprints of adsorbates. It typically gives Raman signal enhancements of the order of 10^4–10^9, although enhancements as high as 10^{14}–10^{15} have been reported for single-molecule SERS. Many enhancement mechanisms have been proposed, but it is generally accepted that the largest enhancements arise from electromagnetic factors because the local Raman signal scales as the fourth power of the local electromagnetic field amplitude. An accurate description of electromagnetic fields near metal surfaces is therefore critical for understanding SERS. Although it is well accepted that the local electric field is greatly enhanced in the vicinity of metal nanoparticles, the effects of local field gradients on SERS are less well understood although some SERS substrates potentially generate substantial electric field gradients.

Writing in *Nature Photonics*, Mai Takase and co-workers[1] now report the observation of surface-enhanced resonance Raman scattering from a carbon nanotube located between two nanoparticles. Surface-enhanced resonance Raman scattering is a variant of SERS in which the incident photon energy is in resonance with both the molecular excited state and metal excitations. However, in the experiment by Takase *et al.*, the ground-to-excited state transition in the carbon nanotube is dipole forbidden. They present evidence that suggests the field-gradient effect is responsible for the observed spectra. Indeed, their experiment seems to provide the clearest evidence to date that field gradients affect SERS.

Interest in the field-gradient mechanism initially arose in the early 1980s when Moskovits and DiLella[2] noted that benzene-d_6 adsorbed on a silver film exhibits seven vibrational modes that are usually inactive in the Raman spectrum of the free molecule. A possible explanation of these new modes is symmetry lowering to C_{3v} originating from a molecule–surface interaction in which each of the three double bonds in benzene binds to a metal atom. This generally implies a strong interaction with the surface; however, the frequency shifts in the Raman spectrum are very small, which suggests a weak