Two-photon absorption generated by optically amplified signals

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Two-photon absorption generated by band-limited amplified spontaneous emission noise was found to be twice that generated by a continuous-wave optical signal with the same average power. A simple formula for describing the two-photon absorption generated by optically amplified signals has been obtained and confirmed experimentally.

Introduction: Two-photon absorption (TPA), because of its sensitivity to peak modulated signal power, has attracted interest recently for monitoring optical transmission impairments [1]. The photocurrent generated by TPA has been used to measure the signal distortion from both chromatic dispersion and polarisation mode dispersion [1, 2]. Monitoring amplified spontaneous emission (ASE) noise due to optical amplification or the optical signal-to-noise ratio (OSNR) is also desirable, particularly using so-called 'in-band' techniques in transparent networks for which conventional optical spectral monitoring does not provide reliable measurements [3]. Monitoring OSNR within the channel bandwidth (i.e. 'in-band') using TPA is possible as analysed in [1] and implemented in [4]. In [1], however, filtered or band-limited ASE (BL-ASE) noise is assumed to behave as a continuous-wave (CW) optical signal with regard to TPA generation, so that, with the same average power as a modulated optical signal, noise is expected to always produce less TPA. In this Letter, we report that the BL-ASE noise generates TPA twice that generated by a CW optical signal with the same average power. We also give a formula for the TPA dependence on OSNR for the case of optically amplified signals.

Theoretical analysis: A simple semiclassical treatment is applied to this problem, extending the conventional single-photon result [5]. To avoid any complexities caused by the polarisation dependence of the TPA detector, we consider an optical signal and BL-ASE noise in a single polarisation, as might be obtained using polarisation diversity [6]. A modulated optical signal following amplification by an optical amplifier with gain G can be expressed as $s(t) = \sqrt{}(Gp(t)) \exp(j\omega_0 t)$. The TPA photocurrent generated by this modulated optical signal can be expressed as:

$$i_{signal} = C\,\mathrm{Im}(\chi^{(3)})\overline{|s(t)|^4} = C\,\mathrm{Im}(\chi^{(3)})G^{(2)}\overline{p(t)}^2/d_{gen} \tag{1}$$

where $C = el/(4n^2c^2\varepsilon_0 hS)$; l is the absorption length; S is the spot area, n is the index of refraction, e, c, h, and ε_0 are, respectively, the electron charge, speed of light, reduced Planck constant, and permittivity of free space; $\mathrm{Im}(\chi^{(3)})$ is the imaginary part of the third-order nonlinear susceptibility, which is typically polarisation dependent; $\overline{p(t)}$ is the average power of the optical signal input to the amplifier; and $d_{gen} = \overline{p(t)}^2/\overline{p^2(t)}$ is the generalised duty cycle of the modulated optical signal [1]. Note that the optical bandwidth is assumed to be wide enough to encompass the signal bandwidth. Following [5], the BL-ASE noise can be expressed as $n(t) = \sum_{k=-M}^{M} \sqrt{N_k \Delta\nu}\exp(j(\omega_0 + 2\pi k\Delta\nu)t + j\phi_k)$, where N_k is the noise power spectral density, and ϕ_k is a random phase. The average noise power is $\overline{p^{noise}} = \sum_{k=-M}^{M} N_k \Delta\nu$. To find the TPA photocurrent generated by the BL-ASE noise, simplification procedures similar to those in reference [5] can be used to calculate the time and ensemble average of $n^4(t)$, yielding:

$$i_{noise} = 2C\,\mathrm{Im}(\chi^{(3)}) \sum_{i=-M}^{M} N_i \Delta\nu \sum_{i=-M}^{M} N_j \Delta\nu = 2C\,\mathrm{Im}(\chi^{(3)})\overline{p^{noise}}^2 \tag{2}$$

Compared with the formula (1) for modulated optical signals, we see that the BL-ASE noise is expected to generate the same TPA photocurrent as an on–off modulated optical signal with a generalised duty cycle equal to 50% (non-return-to-zero on–off keying, NRZ-OOK). Note that this result is also valid for unpolarised noise if $\mathrm{Im}(\chi^{(3)})$ is polarisation independent. This result is independent of the optical bandwidth and assumes that the TPA bandwidth is infinite.

The TPA photocurrent generated by an optically amplified signal is determined by including the signal-noise beat term. To account for the spectral shape of the modulated optical signal, we express it in a form similar to the BL-ASE noise $s(t) = \sum_{k=-M}^{M} \sqrt{GP_k \Delta\nu}\exp(j(\omega_0 + 2\pi k\Delta\nu)t + j\Psi_k)$, where unlike noise the phase Ψ_k is deterministic, and P_k is the signal power spectral density. Similar to the noise case, the average power of the optical signal is $\overline{p(t)} = \sum_{k=-M}^{M} Pk\Delta\nu$. Using this definition and taking steps similar to those used to obtain (2), the TPA photocurrent corresponding to the signal-noise beat term can be expressed as:

$$\begin{aligned} i_{signal-noise} &= 4C\,\mathrm{Im}(\chi^{(3)})G \sum_{i=-M}^{M} N_i \Delta\nu \sum_{i=-M}^{M} P_j \Delta\nu \\ &= 4C\,\mathrm{Im}(\chi^{(3)})G\overline{p^{(t)}}\,\overline{p^{noise}} \end{aligned} \tag{3}$$

Combining all the above results the TPA photocurrent generated by an optically amplified signal can be expressed as:

$$i_{total} = C\ \mathrm{Im}(\chi^{(3)})\left(2\overline{p^{noise}}^2 + \frac{G^2\overline{p^{(t)}}^2}{d_{gen}} + 4G\overline{p^{(t)}}\,\overline{p^{noise}}\right) \tag{4}$$

Assuming $\mathrm{Im}(\chi^{(3)})$ is polarisation independent and keeping both polarisations of the noise will reduce the third term by $1/4$. Equation (4) can be changed to explicitly depend on the OSNR as

$$i_{total} = 2C\ \mathrm{Im}(\chi^{(3)})p_{total}^2\left[1 + \left(\frac{r}{1+r}\right)^2\left(\frac{1}{2d_{gen}} - 1\right)\right] \tag{5}$$

where $r = 10^{\mathrm{OSNR}/10}(0.1\ \mathrm{nm}/\mathrm{NEB})$, NEB is the noise equivalent bandwidth, and $p_{total} = \overline{p^{(t)}} + \overline{p^{noise}}$. These relationships can be used to determine the TPA monitoring sensitivity to the OSNR for signals with different modulation formats or signal distortion characteristics, resulting in different values of d_{gen}.

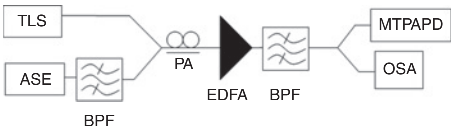

Fig. 1 *Schematic diagram of experimental setup*

TLS: tunable laser source; ASE: amplified spontaneous emission source: BPF: bandpass filter; PA: polarisation analyser; MTPAPD: microcavity TPA photodetector; OSA: optical spectrum analyser

Experiment: The TPA of an optically amplified signal was characterised as a function of OSNR using the experimental setup shown in Fig. 1. An external cavity widely tunable laser provides the CW optical signal. It can also be internally on–off modulated (duty cycle 50%, frequency 200 kHz) to provide the modulated optical signal (i.e. a train of 1-0-1-0 NRZ bits). An Er-doped fibre amplifier (EDFA) acts as the ASE source, which is followed by a bandpass filter (BPF) with a full-width at half-maximum (FWHM) of 1.0 nm to provide the BL-ASE noise. A 50:50 beam splitter is used to combine the CW or the modulated optical signal with the BL-ASE noise and then the noise loaded signal passes through a polarisation analyser (PA, polariser followed by a quarter-wave and half-wave plate pair), another EDFA, another 1 nm BPF, and then 50% goes to the TPA detector, which in our case is a GaAs microcavity TPA photodetector (MTPAPD) [7], and 50% goes to an optical spectrum analyser for average power and OSNR monitoring. The MTPAPD is designed to greatly enhance the TPA photocurrent by placing the absorption region between two highly reflective Bragg stacks. The photocurrent generated in the MTPAPD is measured by a Keithley picoammeter. The PA polarises the BL-ASE noise and ensures that it is incident onto the TPA detector with the same polarisation as the optical signal. Some unpolarised ASE noise from the second EDFA is also present, but is negligible in power compared to the polarised noise. The MTPAPD has a spectral FWHM of 7.1 nm, which is much larger than the bandwidth of the BL-ASE noise. Fig. 2 shows the photocurrent power curves for three incident situations: CW signal-only, 50% on–off modulated signal-only, and noise-only. A clear coincidence of the noise curve and the modulated signal curve can be seen, which demonstrates that for TPA generation the BL-ASE noise is equivalent to an on–off modulated signal with a 50% generalised duty cycle (NRZ-OOK modulated signal). By changing the power of the tunable laser and the ASE source separately, we are able to adjust the OSNR level of the signal. The total power, however, cannot be kept constant in our simple setup. We can eliminate its influence by taking the ratio i_{total}/p_{total}^2 total, for which the variance against

OSNR is shown in Fig. 3. For the modulated signal with the duty cycle $d_{gen} = 50\%$, the TPA response normalised by the total power squared does not change with the OSNR. For the CW case with $d_{gen} = 1$, as the OSNR decreases the normalised TPA response increases. The theoretical curves calculated from (5) agree well with the experiment results.

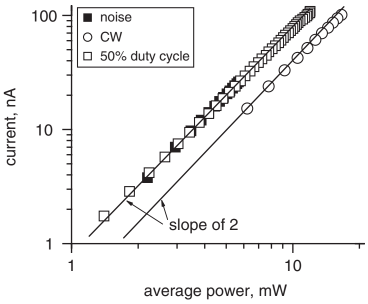

Fig. 2 *TPA photocurrent against average power for BL-ASE noise, CW and 50% on–off modulated signals (NRZ-OOK)*

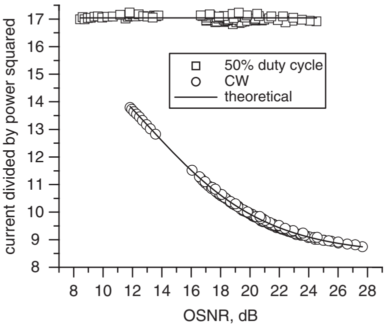

Fig. 3 *Normalised TPA photocurrent against OSNR for combination of BL-ASE and CW or 50% on–off modulated signal*

Conclusions: TPA generated by BL-ASE noise has been shown analytically and experimentally to have the same mean power dependence as an on–off modulated signal with a generalised duty cycle equal to 50%. A simple formula is derived to describe the TPA dependence on the OSNR for an optically amplified signal with polarised BL-ASE noise.

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