Spectral and Temporal Investigations of Nonlinearities in a Non-Polarization Preserving Single-Mode Optical Fibre

A. S. L. Gomes, U. Österberg*, and J. R. Taylor

Optics Section, Blackett Laboratory, Imperial College, Prince Consort Road, London SW7 2BZ, UK

Received 12 March 1986/Accepted 13 August 1983

Abstract. Intense green and red components generated in a non-polarization preserving optical fibre using a Q-switched and mode-locked cw Nd : YAG laser have been examined spectrally and temporally with picosecond resolution. In addition to the red (four-photon interaction) and green (second-harmonic) components, many other frequency mixing processes were detected. From theoretical considerations, the red component (anti-Stokes) which is generated through parametric four photon mixing should be in the same propagation mode as the Stokes component (iir) and this was confirmed experimentally.

PACS: 42.10, 42.65, 42.80

The investigation of laser-induced nonlinearities in optical fibres has become a very attractive way of studying both fundamental physical processes as well as losses associated with practical limitations on the power levels used in fibre transmission systems [1]. Among the most exploited nonlinear effects, frequency conversion by stimulated Raman scattering (SRS) and phase-matched four photon mixing have been studied, and reviews of these and other effects can be found in [1-4]. In the work reported here, we have used a non-polarization preserving fibre (single-mode at 1.06 µm) and examined the nonlinear mixing processes occurring over 1.5 and 120 m lengths. The power-dependent generated spectra in the range 500 nm - 1.35 µm were recorded for each fibre for input peak powers of 1-350 kW from a cw Q-switched and mode-locked Nd : YAG laser. Simultaneous temporal measurements recorded the power-dependent variations in the pulse envelopes of the generated radiation to give an insight to the generation process. Greater temporal resolution was achieved using a synchronously operating streak-camera to examine the intense green component generated in the fibre. The spectra showed, for the higher peak powers, all the different parametric interaction reported so far [1-4] for polarisation preserving optical fibres. In addition, an intense component was generated with high conversion efficiency at 647 nm via a four-photon mixing mechanism with the fundamental (1.06 µm) acting as the pump wave. This corresponds to a measured frequency shift of ~ 6100 cm^-1. Similar shifts have been reported previously for multimode graded-index optical fibres [5].

1. Experimental

The experimental scheme is similar to that reported earlier [7] in studies of Raman generation in single-mode fibres. A Q-switched and mode-locked cw Nd : YAG laser (modified Quantronix model 116) was used as the excitation source, delivering a maximum peak power of ~ 900 kW at 800 Hz Q-switch rate, in 100 MHz repetition rate pulses of ~ 100 ps duration contained within a Q-switched envelope of 250 ns. Operation in the prelase condition ensured stability and reproducibility of the pulses [5]. The fibre was non-polarization preserving, single mode with a 7 µm core diameter and a cut off wavelength at 1 µm. A 7.6% Ge-doping was used in the core with a Δn of 0.008 at 1.06 µm between core and cladding. The excitation

---

* Permanent address: Institute of Optical Research, KTH, S-10044 Stockholm, Sweden
pulses were coupled into the fibre with a typical efficiency of 50% using a standard 20X microscope objective. A 3 m Ebert Spectrograph with a resolution of 0.1 nm was used to record the generated spectra between 500 nm and 1.35 μm. Photomultipliers with S20 and S1 photocathodes were employed in the visible (500-700 nm) and near ir (700 nm-1.36 μm), respectively. All spectra were recorded with the cladding stripped off the input and output ends of the fibre for about half a metre.

2. Results and Discussion

With the 120 m fibre and excitation peak powers up to 100 kW, the well established Raman spectra for silica core fibres ($\Delta\nu=440$ cm$^{-1}$) was obtained between 1.0 and 1.35 μm [1]. For higher peak powers the Stokes components began to reduce in intensity. This was due to depletion through generation of higher Stokes orders and by nonlinear mixing to generate other wavelengths. The effect of depletion on the input 1.06 μm radiation can be seen in Fig. 1 where the time scale for all traces is 200 ns/div. The input train (Fig. 1a) was undistorted on exit for a peak power 1 kW (Fig. 1b). On increasing to ~10 kW (Fig. 1c) the centre was almost totally depleted (through Stokes generation) and this gives an effective pulsetrain broadening, while for 350 kW peak power the pulse train had been depleted almost to the level of the prelase (Fig. 1d). The prelase can be seen to the l.h.s. of Fig. 1d, and clearly illustrates the low threshold for the nonlinear processes. Each generated Stokes component itself showed a similar behaviour, and Fig. 2 graphically represents the effective pulsetrain broadening through depression of the peak for the fundamental and first three Stokes components. A temporal study of the Stokes components with picosecond resolution has been reported elsewhere [7]. Ohmori et al. [8] have previously studied the depletion of the fundamental by generation of the first Stokes component. In the spectral region 0.7 nm-1.0 μm an anti-Stokes continuum from the 1.06 μm pump was produced, while in the range 500-700 nm distinct red and green components were generated, as shown in Fig. 3a 120 m and b 1.5 m fibre length, for peak pump powers in the range 250-300 kW. The component at 532 nm was the second harmonic of the 1.06 μm pump and was measured to have a conversion efficiency of 0.03% for the 1.5 m fibre. In addition to the strong green, an intense red component at 647 nm together with other

Fig. 1a-d. Power-dependent pulse envelope variation: (a) input pulse train and output waveform for input peak powers of (b) 1 kW, (c) 10 kW, (d) 350 kW to 120 m fibre. All time calibration 200 ns/div.
weaker lines (Fig. 3a and b) were recorded. The conversion to the red band occurred with similar efficiency as that of the second-harmonic generation. It is postulated that the phase-matched four-photon mixing process represented in (1) could be responsible for the main red line:

\[ 2\alpha_{\text{L}0.66\mu m} = 3\alpha_{\text{L}0.0017\mu m} + 3\alpha_{\text{L}0.0017\mu m}. \]  

(1)

Both SRS and four-photon mixing processes arise from the third-order nonlinear susceptibility [1-4], SRS being related to the imaginary part of \( \chi^{(3)} \) whereas the four-photon mixing is due to the real part. For this reason, both effects can occur simultaneously in a fibre, although it may not necessarily be the case. Stolen and Björholm have shown [2] that there is a characteristic length \( L_c \) above which SRS dominates, whereas for lengths of the order of, or less than, \( L_c \), the four-photon mixing process plays a major role. The characteristic length can be determined from [2]

\[ L_c = \frac{2\pi}{\Delta\nu} \left[ 4\pi D(\lambda)\Delta\nu \right]^{-1}, \]  

(2)

where \( \Delta\nu \) is the pump linewidth in cm\(^{-1} \), \( \Delta\nu \) is the phase-matched frequency shift and \( D(\lambda) = cD \) being the group-velocity dispersion for the medium in units of ps/nm/km. From the measured frequency shift, it is then straightforward to calculate \( L_c \) from (2). For a pump line width of 0.3 cm\(^{-1} \), \( \lambda = 1.06 \mu m \), \( D(\lambda) = 0.012 \) and a measured \( \Delta\nu = 6100 \text{ cm}^{-1} \) the calculated value for \( L_c \approx 2.2 \text{ m} \). This is in agreement with our observation for the two different fibre lengths. As can be seen in Fig. 3a, for 120 m of fibre the four-photon mixing is present (the line at 647 nm). However, due to the dominant presence of SRS, it is substantially less intense than that observed for 1.5 m of fibre (Fig. 3b) as it should be expected if the fibre length is such as to enhance the four-photon mixing process. In addition, the lines forming the band-like spectrum (Fig. 3a) around 653 could possibly be due to four-photon mixing process with one of the Raman lines acting as the pump. A recently reported experiment [9] would support this consideration. In it, a four-photon mixing process in a birefringent fibre generated lines around 600 nm when pumped by either 1.06 or 1.17 \( \mu m \). The same authors also observed the line at 556 nm which in our measured spectra is at 557 nm for the 120 m of fibre and 557 for 1.5 m, the discrepancy (~1 nm) being, possibly due to experimental error is thought to be due to some cascade four-photon mixing process rather than a three-wave process proposed in [10, 11].

A simple calculation was performed to investigate whether the phase-matched process of (1) would be a plausible explanation for the observed generation at 647 nm. Phase-matching of parametric interactions involving large frequency shifts can be accomplished by means of combining the modes for the pump, Stokes and anti-Stokes such that [1, 2]

\[ f(\Delta\nu) + JK = 0. \]  

(3)
In (3), \( \Delta f(\Delta x) \) is the phase mismatch due to the waveguide dispersion, given by

\[
\Delta f = 2\pi f \text{m} \left( \frac{\beta_1''(0)-\beta_1''(\frac{\lambda_0}{2})}{\lambda_0} + \frac{\beta_1''(\frac{\lambda_0}{4})}{\lambda_0} - \frac{2\beta_1''(0)}{\lambda_0} \right) \tag{4}
\]

and \( \Delta K \) is the phase mismatch due to the material dispersion, which can be calculated using the expression:

\[
\Delta K = 2\pi \left( \frac{\beta_1''(0)+\beta_1''(\frac{\lambda_0}{2})-2\beta_1''(\frac{\lambda_0}{4})}{\lambda_0} \right) \tag{5}
\]

In (4), \( b \) is the normalized propagation constant and all the other parameters in (4 and 5) have their usual meaning. Figure 4 shows a plot of the normalized propagation constant \( b \) as a function of the normalized frequency for the 01 mode of a stepped index fiber. Propagation of both pump, Stokes and anti-Stokes in the same (LP21) mode is required as the only possible way of explaining the above process. It was experimentally confirmed (at the red (647 nm) line) propagated in this mode. Figure 5 shows a plot of material dispersion \( \Delta K \) and waveguide dispersion \( \Delta f \) as a function of \( \Delta x \). The refractive indices were calculated from a three-term Sellmeyer dispersion equation, and constants for the Sellmeyer equation were taken from [12, 13] in order to cover the spectral range of interest of our experiment. From Fig. 5, the theoretical value for the frequency shift \( \Delta x \) in order to satisfy (3) is inferred to be \( \sim 6600 \text{ cm}^{-1} \) which is in reasonable agreement with the observed value of 6100 cm\(^{-1}\). The Stokes shifted component at \( \sim 3 \mu \text{m} \) was not detected due to the lack of adequate detector. However, it would be unlikely to be seen, since it falls in the region where the broad OH vibration at 2.9 \( \mu \text{m} \) will give rise to substantial absorption, although it has been shown that the anti-Stokes frequency generation would be efficient even if the Stokes radiation undergoes strong absorption [14]. An estimate of the parametric gain \( \alpha \) and the coherence length \( \chi_{\text{coh}} \) using the equation given in [2], shows values of \( \alpha = 2 \times 100 \text{ cm}^{-1} \) and \( \chi_{\text{coh}} = 108 \text{ cm} \). It should be noted that for the highest input peak powers (300 kW) launched into the fibres, the corresponding power density was \( \sim 1 \text{ TW cm}^{-2} \) which is in the region of the threshold for optical damage of the fused silica core. Consequently damage to the fibre input occurred, and for the short (1 m) length, the damage appeared to be caused in the core throughout the complete fibre length.

In addition to the four-photon mixing process, we observed third-harmonic generation and three-wave mixing lines of the fundamental and it Stokes radiation to uv. In Fig. 6, a spectrum representative of this feature is shown for a fibre length of 1.5 m and input peak power of \( \sim 300 \text{ kW} \). The lines have been identified as well as the main harmonic (3), as indicated in the inset of Fig. 6. This result agrees with
the observations of Gabriques [15] obtained with polarisation preserving fibres.

The temporal width of the second harmonic was also measured using a streak scan strip camera. The result is shown in Fig. 7. For a fixed input power (50 kW) the recorded fundamental (a) and second harmonic (b) pulse widths are shown. It can clearly be seen that the ratio of the pulse widths of second harmonic and fundamental does not follow the \( \frac{1}{2} \) factor characteristic of a dipole type process of second-harmonic generation (most common in noncentrosymmetric materials). However, because the SiO\(_2\) based optical fibre is, in principle, centrosymmetric, the process for second-harmonic generation would have to be other than a dipole interaction. A quadrupole process is thought to be more likely [4] and our pulse-width measurement could support this assumption.

However, a more detailed study is necessary to understand second-harmonic generation in optical fibres, both theoretically and experimentally. Anisotropy caused by imperfections during the fabrication process or strain induced birefringence could be possible causes [4] for an enhancement in the second-harmonic process. We have observed that the intensity of the second harmonic "grows in", increasing with time to stabilise at a constant level after a few hours and that the "processing" of the fibre is stable in the long term in that SHG is immediate up to 24 hours later. We have also measured the power variation of the pulsedwidth of the green light emitted from the fibre, both in the picosecond regime (each pulse within the envelope) and the pulstrain itself (a few hundreds of nanosecond). This is shown in Fig. 8, and it can be seen that a saturation of the duration of both the pulstrain and the single pulse is evident.

3. Conclusions

In summary, we have reported on a spectral and temporal study of propagation of picosecond laser pulses in Ge doped single-mode silica core optical fibres. Different lengths (120 m, and 1.5 m) were used and peak power up to \( \sim 300 \) kW were launched into the fibres, thus permitting very intense nonlinear interactions. Parametric four-photon mixing, second- and third-harmonic generation as well as three-wave mixing have been observed. A theoretical calculation of the four-photon mixing process has been performed and the results are in reasonable agreement with the experimental measurements. A temporal study of the second-harmonic component was carried out using a synchronously operating streak camera and a factor of two broadening in pulse width for the green component has been recorded as the power was increased. The process for the emission of second-harmonic radiation from the single-mode non-polarisation preserving optical fibre still remains to be totally understood and we hope the temporal measurements reported here should add some information to the origin of this process. Finally, it should be noted that high efficiencies (0.5%) second-harmonic generation have been reported recently for a similar fibre type as the one employed here [16].

Acknowledgements. Financial support from the Science and Engineering Research Council is gratefully acknowledged. Postgraduate support for one of us (A. S. L. Gomes) by the CNPq (Brazilian Agency) and overall financial support for another (E. Österberg) by the Swedish Natural Science Research Council (NFR) is also gratefully acknowledged.
References