Slow light generation in singlemode Er-doped tellurite fibre

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The efficient generation of slow light in a singlemode Er-doped tellurite glass fibre, which has a Brillouin gain coefficient about an order of magnitude larger than silica fibre is reported. Pulses of 60 ns width were delayed by 67 ns in a 2 m length of fibre with a pump power of 630 mW. The large Brillouin gain and relatively low loss of tellurite fibre should be useful in the realisation of compact slow light devices operable at a lower pump power.

Indroduction: Slow light generation by stimulated Brillouin scattering (SBS) [1–3] in optical fibres has attracted considerable attention lately as a candidate for realising optical buffers in next-generation all-optical networks. This is attractive for optical communication systems, because of its compatibility with installed fibre-optic systems and its ability to operate at arbitrary wavelengths and temperatures. The large Brillouin gain that occurs in a narrow bandwidth (several tens of MHz) leads to a large increase in the group index, which can be utilised to delay pulses with widths of the order of tens of nanoseconds. For delaying narrower pulses (such as tens of picoseconds of width), a wider gain bandwidth is required, which can be attainable through optical frequency modulation and use of multiple pumps [4]. Such modulation in the pump frequency however, demands higher pump power to achieve the necessary gain. Recently non-silica-based fibres with large Brillouin gain coefficients have been found suitable for slowing down light in short lengths of fibre. A delay of 37 ns was achieved in a 5 m length of As_2Se_3 fibre with a pump power of 60 mW [5], while a delay of 46 ns was achieved in a 2 m length of bismuth fibre for a pump power of 410 mW [6]. In these experiments, the length of the fibres were limited to a few metres owing to the relatively large loss in the fibre, which prohibited further reduction in pump power by using a longer fibre. It has been reported earlier that singlemode fibre can be drawn from tellurite glass with a background loss as small as 0.02 dB/m [7], much smaller than those of other non-silica fibres, such as bismuth, chalcogenide glass fibres. Moreover, our recent observation of large Brillouin gain coefficient in tellurite glass suggested that tellurite fibre could be potentially useful towards the realisation of compact slow light devices operable at low pump power [8].

In this Letter we experimentally generate slow light in singlemode erbium-doped tellurite glass fibre using its large Brillouin gain coefficient. By launching 630 mw of continuous-wave Brillouin pump light at 1542 nm, we could amplify the Stokes wave by as much as 52.5 dB in a 2 m-long fibre. A delay of 67 ns could be achieved for Stokes pulses with widths of 60 ns, showing a fractional delay of 1.1.

Experiment: In our experiment, we used singlemode tellurite fibre (NTT Electronics), which had a core diameter of 2.6 μm, Δn of 1.6%, and a cutoff wavelength of about 1.3 μm. The tellurite fibre which was available to us, was doped with erbium to a concentration of about 1000 ppm (wt%). Owing to the doping, the fibre exhibited large loss (greater than 35 dB, as measured in a 2 m length of fibre) at low pump power (less than −5 dBm) at a pump wavelength of 1542 nm. However, at higher launched power, the fibre became increasingly transparent as loss began to saturate. For a pump power of 25 dBm, we estimated a loss of 0.51 dB/m (i.e. $\alpha = 0.117\ \mathrm{m}^{-1}$) [9]. The tellurite fibre was coupled to a silica fibre using a tilted V-groove connection [7] with an estimated coupling loss of about 0.6 dB. When a weak probe signal (frequency up- or down-shifted by ν_B with respect to the pump using optical phase modulation) was launched into the tellurite glass fibre in a direction opposite to the strong pump wave, a large change in the intensity was observed owing to SBS in the fibre.

Fig. 1*a* shows the intensity change with the Stokes and anti-Stokes waves at different modulation frequencies, giving a Brillouin shift of 7.882 GHz. A Brillouin gain, $10\log[\exp(g_B L_{eff} PK/A_{eff})]$, of 30 dB was obtained for a pump power of 360 mW, which corresponded to a gain of 0.083 dB/mW of the pump power. A Brillouin gain coefficient of 1.47×10^{-10} m/W was obtained using the effective area $A_{eff} = 9.18\ \mu\mathrm{m}^2$ and effective length L_{eff} (= 1.78 m of the fibre) and a polarisation factor $K = 0.667$ [8]. Also, by fitting the gain curve in Fig. 1*a* with a Lorentzian profile, a 3 dB linewidth, $\Delta\nu_B$, of 23 MHz was obtained. Fig. 1*b* plots the peak intensities of the Stokes and anti-Stokes modulating sidebands ($f_m = \nu_B =$ 7.882 GHz) against pump power. The gain increased linearly with pump power to about 500 mW, beyond which gain began to saturate. A maximum gain of about 55 dB was achieved using a pump power of 800 mW.

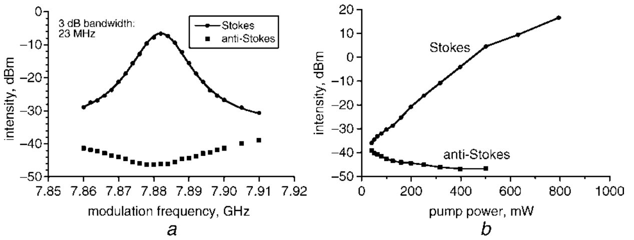

Fig. 1 *Brillouin amplification and attenuation in 2 m-long tellurite fibre experienced by Stokes (circle) and anti-Stokes (squares) component owing to SBS*

a Intensity change against modulation frequency
b Intensity change against pump power

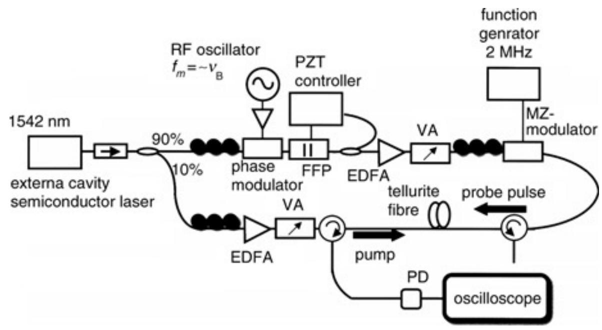

Fig. 2 *Experimental setup used for slow light generation*

The experimental setup used for the slow-light generation is shown in Fig. 2. Continuous-wave (CW) laser radiation at ∼1550 nm from an external-cavity semiconductor laser was divided into two parts. One part was amplified for use as a CW pump, whereas the other part was phase-modulated using an RF oscillator at a frequency of 7.882 GHz ($=\nu_B$). The Stokes frequency component, after being extracted using a fibre Fabry-Perot (FFP) filter (FSR: 154 GHz, bandwidth: 750 MHz), was then intensity-modulated using a Mach-Zehnder modulator to produce Gaussian probe pulses with a width of about 50 to 60 ns at a 1 MHz repetition rate. The pulsed output was launched into a 2 m long tellurite fibre in a direction opposite to that of the pump. Note that besides the 1542 nm Brillouin pump laser, no other pump in the 1480 or 980 nm bands was employed in the experiment.

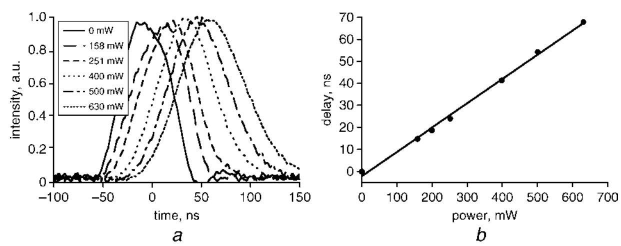

Fig. 3 *Waveforms of Stokes pulses observed at fibre output*

a Waveform at different pump power
b Delay against pump power

Fig. 3*a* shows the waveforms, normalised to the peak power, of the output probe pulses observed at different launched powers. To avoid the effect of gain saturation in the fibre and in the photodetector, we gradually decreased the amplitude of the initial probe pulse using a variable attenuator to keep the same probe power on the photodetector regardless of the gain. A shift in the peak by as much as 67 ns (1.1 times the pulse width) was measured for the 60 ns pulses, as the pump power was raised from 0 to 630 mW (a gain change from 0 to 52.5 dB). Fig. 3*b* plots the measured delay in the probe pulses for different pump powers. From the slope of the curve and the effective length of 1.78 m, we obtained a delay generation efficiency of 0.06 ns/mW/m.

This is in good agreement with the value 0.071 ns/mW/m predicted theoretically from $g_B K/(2\pi A_{eff}\Delta\nu_B)$ using $A_{\mathrm{eff}} = 9.18\ \mu\mathrm{m}^2$, $K = 0.667$, $\Delta\nu_B = 23.8$ MHz, and $g_B = 1.47 \times 10^{-10}$ m/W [8, 9]. The efficiency of the delay generation observed in our tellurite fibre with A_{eff} of 9.2 $\mu\mathrm{m}^2$ is about the same as that reported in a small-core bismuth fibre (A_{eff} =3 $\mu\mathrm{m}^2$) [6], and about 30% of that achieved in an As_2Se_3 fibre (A_{eff} = 39 $\mu\mathrm{m}^2$) [5].

Although in the experiment we have used erbium-doped tellurite fibre, the delay generation efficiency in undoped tellurite fibre should exhibit similar values. Consequently, using a longer piece of undoped tellurite fibre (a few tens to a few hundred metres), which reportedly has a much lower loss (0.02 dB/m), one should be able to reduce the pump power by one or two orders of magnitude.

Conclusion: We have demonstrated efficient pulse delaying using SBS in tellurite glass fibre. The fibre had a Brillouin gain coefficient about an order of magnitude larger than that of conventional silica fibres. A maximum delay of 67 ns was achieved using 60 ns pulses in a 2 m length of fibre with a pump power of 630 mW. Further enhancement in efficiency or reduction in pump power should be possible through the use of undoped tellurite fibres with lower losses.

31 July 2007
Electronics Letters online no: 20082230
doi: 10.1049/el:20082230

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