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Noise characteristics of cross-phase modulation instability light

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The noise characteristics of cross-phase modulation instability visible light produced in high-birefringence fibres have been investigated. Noise measurements were made on single sidebands, and on the intensity difference between upshifted and downshifted sidebands using single pass and fibre-laser configurations. The intensity difference noise for the single pass configuration was reduced by more than 25 dB below the single sideband noise, which was typically 35 dB above shot noise. Under certain conditions the intensity difference noise of the modulation instability laser sidebands could be reduced to the shot noise level, while the single sideband noise from the modulation instability laser could be reduced to 2 dB above shot noise. Raman gain on the low frequency sideband and attenuation in the fibre limited the attainable noise reduction.

1. Introduction

The intensity noise characteristics of cross-phase modulation instability light produced in a high-birefringence pure silica core optical fibre have been investigated. The four-wave mixing spectra were observed on the light exiting the fibre, which was pumped with intense pulses at $\lambda=514.5$ nm from a mode locked, cavity dumped argon ion laser [1]. The sidebands were separated from the pump frequency by about 2.3 THz. The intensity noise on the sidebands, and the noise on the intensity difference, were investigated for the case where the light is produced from a single pass through the fibre, and for the light from a modulation instability laser [2]. In principle the modulation instability process provides a new source of correlated photon pairs, and possible intensity difference squeezing [3].

Initial experiments were performed to investigate the noise on the sidebands produced in a single pass through the fibre. It was found that even though strong correlations could be demonstrated between the noise characteristics of the two sidebands, the natural noise level of these sidebands was so great that sub shot noise levels for the intensity difference noise (produced by electronic subtraction) could not realistically be expected. These high noise levels were not a unique characteristic of the modulation instability process, but rather were similar to the noise levels generated by other processes which are initiated by quantum noise. A similar situation exists, for example, in the noise on the signal or idler waves produced in a single pass optical parametric amplification experiment and also in the noise on the stimulated Raman scattering sideband produced in the same fibre as that with which the modulation instability experiments were performed.

In order to achieve lower noise levels in each sideband, the noise characteristics of a modulation instability laser were also investigated. In order to generate a modulation instability laser, a fraction (~1%) of the modulation instability sideband pulses was fed back into the front of the fibre synchronously with the next pump pulse. The noise was found to exhibit a strong dependence on feedback parameters, which also affected the spectral characteristics of the sidebands. While low noise levels for the sidebands could be achieved by careful adjustment of the (fibre) laser, the noise levels also approached those of the single pass case for other alignments. One of the major obstacles to the observation of intensity difference squeezing, was the Raman amplification of the low frequency sideband which was less in the laser configuration than for the single pass case, since the modulation instability laser could be operated at substantially lower pump power than was needed to

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generate comparable power in the sidebands for the single pass case. In addition, the dispersion tuning of the cavity effectively discriminated against any stimulated Raman pulses, further improving the noise level on the difference of the modulation instability laser sidebands when compared with that of the single pass sidebands.

In both the single pass and the laser configuration the intensity difference noise was never observed to be below the shot noise level. The correlation was certainly limited by stimulated Raman scattering but also by a large attenuation within the fibre. Losses in the optics external to the fibre also contributed to limiting the noise reduction, as did the quantum efficiency of the photodiodes (75%). Section 2 contains a description of the experimental configuration. Section 3 describes the results for single pass modulation instability light, while sect. 4 presents the modulation instability laser results. A discussion of the results and the circumstances preventing further noise reduction is presented in sect. 5.

2. Experimental setup

The experimental configuration for the noise measurements on the modulation instability sidebands generated via a single pass through the fibre is displayed in fig. 1, while the setup for the modulation instability laser experiment is displayed in fig. 2. The pump was a mode locked, cavity dumped argon ion laser, operating at $\lambda = 514.5$ nm. The generated pulses have a peak intensity of up to 1 kW, and a pulse duration of approximately 35 ps [4]. The pulses were generated at a repetition rate of (38.4 MHz)/N, where N is the divide by integer ($N = 2, 3, 4, \ldots$). The modulation instability laser was also operated with the pump laser simply mode locked with a repetition rate of 76.8 MHz. At this pump rate, four pulses circulated in the ring laser simultaneously, each of which propagated independently.

The polarization of the incoming beam was adjusted with a $\lambda/2$ plate. A 10 m, high birefringence, pure fused silica core single mode fibre was used to generate the modulation instability. The index difference between the two fibre axes was $\delta n = 3.25 \times 10^{-4}$, the group velocity dispersion $\beta = 0.069$ ps^2/m at $\lambda = 514.5$ nm, the core diameter

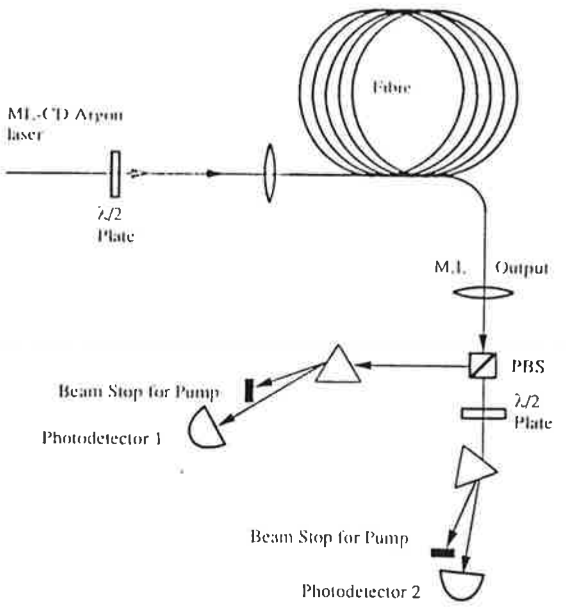

Fig. 1. Schematic diagram of the experimental system used for the single pass for the modulation instability experiment. The modulation instability sidebands are created via a single pass through the fibre pumped by a mode locked, cavity dumped argon ion laser. Intensity difference noise is measured on the electronically subtracted output of the two photodetectors.

was 2.2 μm, the nonlinear refractive index $n_2 = 3.2 \times 10^{-20}$ m^2/W, and the attenuation was 140 dB/km. The attenuation, core diameter and the beat length (from which δn was determined) were quoted by the suppliers [5]. The quoted index difference was consistent with the separation of the pump pulses on the two axes after traversing the fibre (determined using a sampling streak camera). In the modulation instability laser configuration, a small fraction of the output of the fibre was coupled back into the input end of the fibre via a glass plate acting as a beamsplitter. The outputs from the two axes of the fibre were separated with a polarizing beamsplitter, while the sidebands (each having a wavelength difference of 2 nm from that of the pump) were separated from the pump with high dispersion prisms. One sideband had its polarization rotated with a $\lambda/2$ plate to minimize reflection losses on the prisms. The beams were detected with an EG&G model FND-100 photodiode, where the dc current was monitored, and the ac signal was amplified and measured on an rf spectrum analyzer. For the intensity difference measurement, the ac signals from the two detectors were subtracted from one another with a

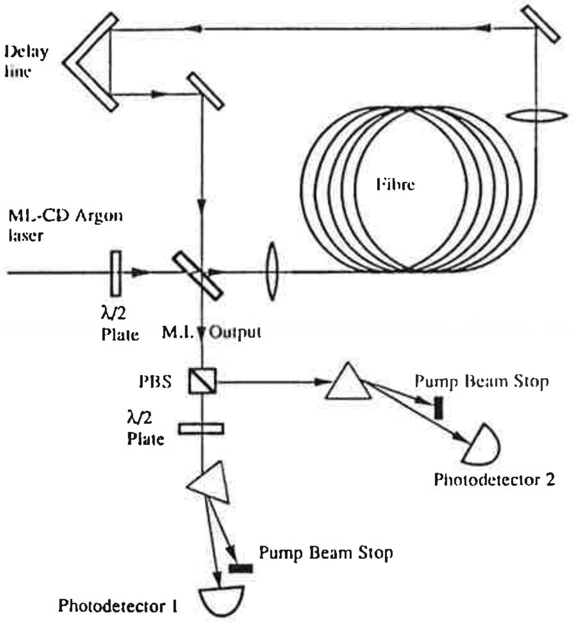

Fig. 2. Schematic diagram of the experimental system used for the modulation instability fibre laser experiment. The modulation instability sidebands are created via a modulation instability fibre laser pumped by a mode locked, cavity dumped argon ion laser. Intensity difference noise is measured on the electronically subtracted output of the two photodetectors.

hybrid junction (ANZAC model HH-107) and the difference was amplified with a transimpedance amplifier (Phillips NE5212). An electronic filter was used to remove the frequency corresponding to the repetition rate of the laser, thereby preventing amplifier saturation. Different wavelengths within the sidebands were selected by using slits after the prism. In attempting to observe subshot noise levels, the current noise of the amplifier was the dominant problem since the difference noise level improved as the pump power was reduced. This current noise contribution was $2.5\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$, corresponding to a shot noise sensitivity limit of 60 μW. The shot noise level was calibrated with an incandescent white light lamp, a cw argon ion laser at $\lambda = 514.5$ nm, and the intensity difference of the mode locked, cavity dumped argon ion laser. The photodetectors had a quantum efficiency of 75%. For the single pass experiment 90% of the light generated by the fibre reaches the photodiode. In the laser configuration a further 8% was lost due to the beamsplitter, and another 8% from the delay line optics.

3. Single pass measurements

Figure 1 displays the layout for the single pass modulation instability experiment. The lowest noise level for a single sideband was measured to be 35 dB noisier than the pump beam for frequencies above a few MHz. The noise level on the pump laser was found to vary between shot noise and 6 dB above shot noise, depending on the adjustment of the phase and delay settings for the cavity dumper and the configuration of the pump laser [6]. Figure 3 displays the measured noise for the two sidebands with respect to the shot noise level. The sideband noise levels are about 35 dB above this level which is consistent with theoretical predictions [7]. The average power in each sideband was 100 μW, while the peak pump power exiting the fibre was about 180 W. The sideband noise tended to increase as the power level for the sideband increased. At 300 μW of sideband average power for example, the noise rose to 45 dB above the pump noise. In addition, the frequency downshifted sideband tended to be 1–2 dB noisier than the upshifted sideband. The wavelength width of the sidebands was 0.5 nm. Very similar results were obtained in measurements of the stimulated Raman

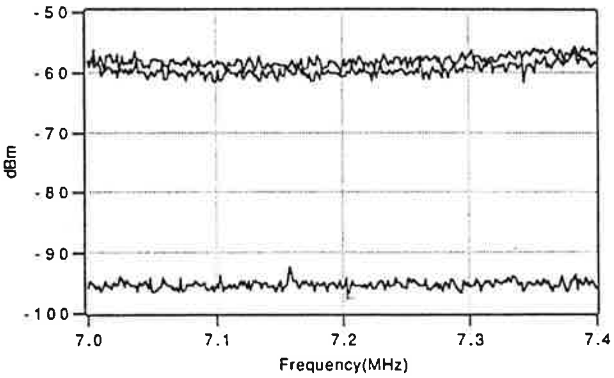

Fig. 3. Noise power spectra for the modulation instability sidebands generated via a single pass through the fibre. The ac photocurrent was passed through an electronic filter to remove the frequency corresponding to the repetition rate of the laser. It was then amplified before analysis by the rf spectrum analyzer. The resolution and video bandwidth was 3 kHz. The average power in each sideband was 100 μW and the peak pump power was 230 W. The bottom trace shows the shot noise level, generated with an incandescent white light lamp. The top trace shows the noise level of the lower frequency (downshifted) sideband, while the middle trace displays the noise on the upshifted sideband. The sidebands are about 35 dB above the shot noise limit.

scattered light generated in the same fibre by aligning the pump polarization with one of the fibre axes. The stimulated Raman sideband generated in this experiment (when separated from the pump using the same experimental setup as that depicted in fig. 1) was also 35 dB above the shot noise level for the same average power as that used to generate the traces in fig. 3. It is also worth noting that the noise of the modulation instability sidebands did not change when the fibre was cooled with liquid nitrogen, although the sideband separation from the pump increased from 2.3 THz to 3.5 THz.

A strong correlation in the noise of the two sidebands was observed via an intensity difference measurement. The noise on the subtracted signal was observed to be reduced by more than 25 dB from the noise of an individual sideband, as shown in fig. 4a. The bottom trace displays the amplifier noise, the next trace the noise on the intensity difference, while the top trace shows the noise when one of the sideband beams is blocked. The noise levels for the two sidebands were within one decibel of each other in this experiment. Adjustable slits were used as spectral filters on the sidebands and a good noise subtraction was only possible for low pump power and consequently low sideband power levels. Figure 4 corresponds to an average power of 7 μW in each sideband, and a peak power of the pump pulse through the fibre of about 100 W (the shot noise level corresponding to 7 μW was below the amplifier noise for our detection system). Similar results were obtained when the average sideband power was 17 μW. The noise on the subtracted signal in this case was 22 dB below the single sideband noise (fig. 4b) showing that as the power of the sidebands increased, the correlation decreased. In part this was due to Raman scattering, since the downshifted sideband is within a region where it can experience Raman gain, while the upshifted sideband is not.

4. Modulation instability laser measurements

The Raman gain and its deleterious effects can be reduced by operating with less pump power. This can be achieved by generating the modulation instability sidebands in a laser configuration [2] which also has the advantage of reducing the noise on the individual sidebands. The positive feedback in the cavity provides a seed for the modulation instability gain, and allows measurable sidebands to be generated with much lower pump powers. In our experiments a small amount of the light leaving the fibre was fed back into the front of the fibre synchronously with the next pump pulse using a glass plate, thus generating a synchronously pumped ring laser (fig. 2). In the low pump power limit, the sideband pulses have the same group velocity as the pump pulse on the other po-

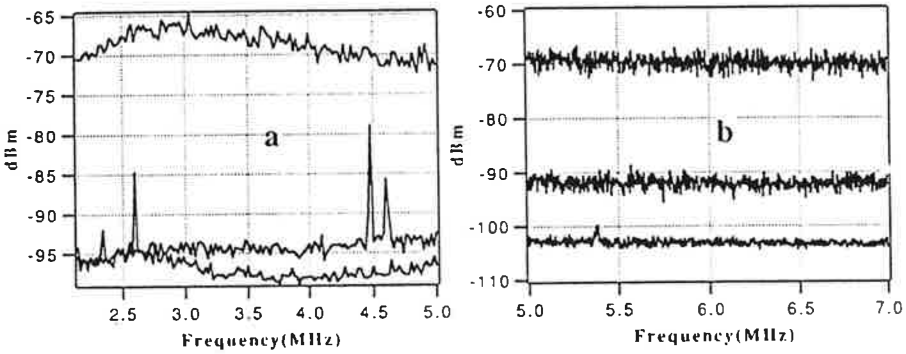

Fig. 4. (a) Noise power spectra for the intensity difference noise on the modulation instability sidebands from a single pass through the fibre. The ac output of the two photodetectors was input directly to a hybrid junction which subtracts one signal from the other. The subtracted signal was electronically filtered and amplified before analysis by the spectrum analyzer. The video and resolution bandwidth was 10 kHz. The lower trace shows the amplifier noise. The middle trace displays the noise for the modulation instability intensity difference with 7 μW of light on each photodiode. The upper trace displays the noise when one of the sideband beams was blocked. The intensity difference noise is more than 25 dB below the single sideband noise (the noise spikes at 2.5 and 4.5 MHz are generated by the cavity dumped pump laser). (b) Noise power spectra as for (a) but with a higher power pump and modulation instability sidebands with a power of 17 μW. The intensity difference noise is approximately 22 dB below the single sideband noise.

larization axis, and would thus separate by approximately 10 ps in the length of fibre used here. In our experiment the two sidebands were fed back with the same cavity length, which together with the polarization of the pump beam, was adjusted to generate the most symmetrical sideband power distribution. This involved optimising the upshifted sideband which did not experience Raman gain. This optimal launch angle for the MI laser experiments was generally close to 30° (relative to the fast axis) corresponding to a pump power on the fast axis twice that on the slow axis. Using this configuration it was possible to lower the noise of a single modulation instability sideband to less than 2 dB above shot noise (fig. 5).

The noise of the sidebands was also strongly dependent upon the noise characteristics of the pump laser. In order to reduce the noise of the fibre laser it was naturally desirable to have the pump laser at the shot noise limit. In the case of the mode locked argon laser, this was possible with careful adjustment of the cavity length [6], but only when the laser was run in a noncavity dumped configuration. With this pump laser, the average power of the sidebands was 330 μW, while the peak pump power exiting the fibre was about 25 W. The noise reduction for a single sideband was also found to be a sensitive function of the feedback parameters of the modulation instability laser. Minimum noise corresponded to very low levels of feedback, which also generated sidebands of minimal width. The low noise sidebands had a wavelength spread of less than 0.1 nm. If the feedback parameters were adjusted to increase the spectral width of the sidebands to 0.5 nm, the single sideband noise was found to increase to 35 dB above shot noise.

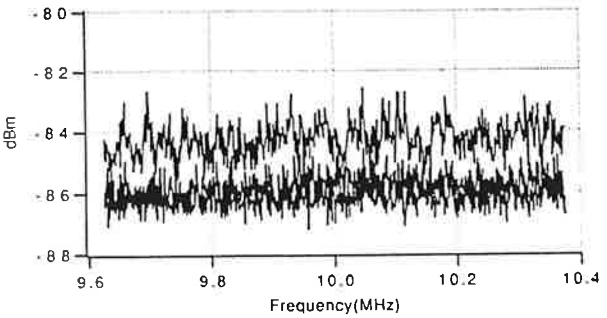

Fig. 5. Noise power spectra for a single sideband from the modulation instability fibre laser (top trace). The sideband noise was 2 dB above the shot noise level which is shown in the lower trace. The average power per sideband is 330 μW, while the peak pump power was 25 W. Video and resolution bandwidth was 30 kHz. The noise trace for the mode locked argon ion laser is also shown just above the shot noise level, and the noise of the difference of the two sidebands was also essentially at the shot noise limit.

Since the single sideband noise for the modulation instability laser could be reduced to within a few dB of shot noise, and noise subtraction of 25 dB had been demonstrated for the single pass modulation instability experiment, the modulation instability laser provided a more promising candidate for demonstrating subshot noise levels than a simple fibre. In our experiments however, while the modulation instability difference noise could be reduced to the shot noise level, this was only possible for small sideband powers using a mode locked cavity dumped pump laser. With 60 μW of light on each photodiode, for example, the modulation instability intensity difference noise and the shot noise levels were equivalent. At no time were we able to reduce the noise below the shot noise level, and for the maximum noise reduction it was necessary to use slits to filter the spectrum of the light incident on the photodetector. The lowest noise was achieved by filtering out the part of the modulation instability sideband that had its wavelength nearest to that of the pump. This filtering reduced the sideband power by about 25%. It should be noted that while the mode locked laser pump provided the lowest noise single modulation instability sideband amplitude noise (corresponding to the fact that the pump laser was itself shot noise limited), we were unable to demonstrate noise reduction in the difference of the intensities of the modulation instability sidebands with this pump source. This is probably due to the fact that there are the four modulation instability pulses in the ring fibre laser when this laser was used as a pump source, and these pulses may fluctuate independently. In comparison, the mode locked cavity dumped pump laser, while generating pump pulses at the fundamental repetition rate of the fibre laser cavity, was always above shot noise for the experiments reported here [6].

5. Discussion

These experiments were undertaken to investigate the possibility of generating intensity difference squeezing via the phenomenon of modulation instability in highly birefringent fibres. The results have shown that the noise characteristics of the two modulation instability sideband beams are indeed strongly correlated. A 25 dB reduction of the intensity difference noise was observed when compared with the noise in a single sideband. The high noise level of these sidebands, when generated via a single pass through the fibre, however, precluded the observation of subshot noise levels. This situation is analogous to that observed when an optical parametric amplifier is used to generate down converted signal and idler beams in a single pass experiment, when high noise levels are also observed. In the parametric amplification process, the noise levels on the signal and idler beam can be greatly reduced by confining the crystal in an optical cavity (i.e. constructing an optical parameter oscillator). This configuration has led to impressive demonstrations of intensity difference squeezing [8]. Subshot noise levels on the intensity difference of the signal and idler beams generated by pulses in an optical parametric amplifier have also been observed despite the noise levels on the individual beams [9].

In our experiments, the noise on one modulation instability sideband could also be greatly reduced by constructing a modulation instability fibre ring laser. In spite of the reduction in noise to only 2 dB above shot noise for the modulation instability laser however, we were not able to demonstrate nonclassical noise levels. The intensity difference noise from the two sidebands of the modulation instability laser could be reduced to the shot noise limit, indicating that the sidebands were strongly correlated, but a further reduction below the classical limit could not be achieved. One important factor limiting the noise reduction was the stimulated Raman gain experienced by the downshifted sideband. This explains the observation that more impressive noise reductions were produced at smaller pump power levels, corresponding to a decrease in the Raman gain on the low frequency sideband. The effect of stimulated Raman scattering is clearly displayed in fig. 6, where the powers of the generated low and high frequency sidebands are plotted against the pump power for the modulation instability laser experiment. Only near the threshold of sideband generation did the two sidebands have equal powers. The power levels were found to diverge as the pump level increased, which contributed to the reduction in correlated noise in the beams. At reduced power levels, the noise levels tended to again increase as the modulation instability laser approached threshold, leading to an optimum pump level for minimum noise. In the single pass configuration, it was not possible to reduce the intensity indefinitely, as the noise measurements became compromised by the contribution of the amplifier noise.

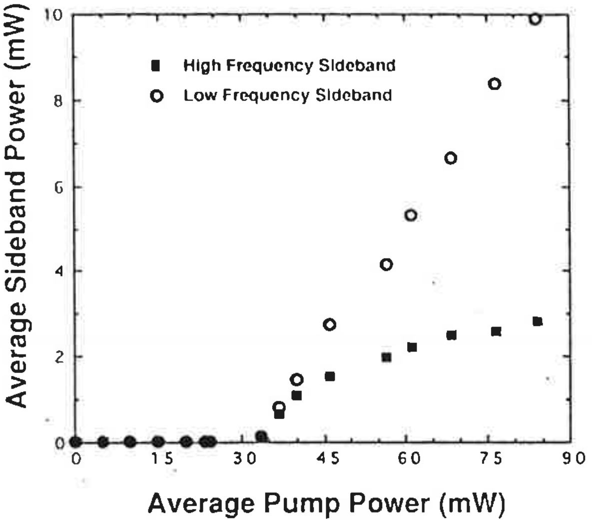

Fig. 6. Power output of the modulation instability fibre laser. The power of the sidebands is plotted against the pump power. The power level of the low frequency sideband quickly diverges from the high frequency sideband as the pump power increases above threshold.

Attenuation in the fibre also contributed to a loss in correlation. To counteract these losses, experiments were performed with shorter lengths of fibre, which also had the beneficial effect of reducing the stimulated Raman scattering. Since the modulation instability gain also decreased however, there was an optimum length of fibre which in our experiments was about 10 m. The fibre used in this experiment was a fused silica core experimental fibre with a depressed index cladding specially designed to avoid the known problems caused by intense green light in germanium doped fibres [10]. Initial experiments with standard germania doped fibres showed that these rapidly develop a substantial loss via two photon absorption caused by the high peak powers used in these experiments. Over time however, we have also observed damage to this special fused silica core fibre by the high peak powers to which it was subjected. Peak powers of over 500 W were coupled into the fibre. Over several months, we observed the transmission capability of our 10 m fibre (including the coupling losses) deteriorate from 65% down to 35%. No suitable replacement for this experimental fibre has been obtained.

Losses external to the fibre were kept to a minimum. For the single pass experiment, at least 90% of the sideband light exiting the fibre reached the photodetectors. In the modulation instability laser configuration there was a further 16% loss due to the glass plate used to feed a portion of the beam back into the fibre, and the delay line optics, while the photodetectors had a quantum efficiency of 75%. These losses, coupled with an estimated loss of nearly 45% for our 10 m damaged fibre gives a total efficiency of only 31%. The amount of squeezing expected for a lossy system is [9]

$$R=1-\eta+\eta R_0 ,$$

where R_0 is the ideal lossless squeezing value and η is the total efficiency. Predicted values for modulation instability intensity difference squeezing noise reduction are of the order of 50% [3], but that would be degraded to a noise reduction value of 15% or 0.7 dB if the system's total efficiency is 31% (it should be noted that this prediction is for a lumped loss system and is not directly applicable to this experiment). The noise on our mode locked cavity dumped laser was also a factor in the experiment. When the mode locked cavity dumped laser is operating where its pulses are the shortest (35 ps) and its peak powers the highest (1 kW) it generally exhibits noise levels about 4 dB above shot noise in the frequency region above 3 MHz. The noise level can be reduced to shot noise, but only at the expense of lengthening the pulses and reducing the peak power, and thereby preventing the generation of the modulation instability light [6]. This noise is a particular feature of the modelocked cavity dumped laser. When the laser was operated as a simple mode locked cavity, the amplitude noise could be reduced to be near to, or at, the shot noise limit. We were unable however, to achieve any intensity difference noise reduction using this laser as a pump source for the modulation instability laser.

The experiments reported here were made possible by the use of a special mode locked argon pump laser which takes advantage of the high peak powers available when the laser operates in the superfluorescent regime [11]. These experiments have shown, that while the demonstration of quantum correlations via modulation instability in optical fibre experiments may well be possible, this will require the use of single photon detection systems, or longer pump wavelengths where the deleterious effects of attenuation in the fibre and stimulated Raman gain are significantly reduced. An ideal pump source for the investigation of these effects would operate at wavelengths longer than 550 nm and be shot noise limited, whilst still achieving peakpowers of the order of 1 kW. In addition it is desirable that the source has a pulse duration long enough to avoid walkoff of the two pump pulses on the fast and slow axes during transit of the fibre. To this end we have recently demonstrated that superfluorescent operation of a krypton laser can be achieved yielding modulation instability at 647 nm in readily available high birefringence fibres. This has overcome the damage problems discussed earlier, and further experiments to demonstrate quantum correlations generated by modulation instability are planned using this source.

Acknowledgements

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