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Non-reciprocal transmission via phase conjugation in multimode optical fibres

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Abstract

We demonstrate phase conjugate correction of modal distortion of a single mode beam on double-passing a passive highly multimode fibre. Phase conjugation is achieved in a self-pumped photorefractive $BaTiO_3$ crystal which conjugates only the e-polarised input component. We show that only a small fraction of the multimode fibre output is required to faithfully conjugate the single mode input beam. This technique enables the demonstration of a novel non-reciprocal transmission device, which for example has immediate application in gain-grating holographic resonator designs with multimode fibres as the active gain medium. © 2001 Published by Elsevier Science B.V.

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1. Introduction

Correction of modal dispersion for light transmitted through multimode optical fibres has been the subject of extensive research to date. At low optical powers photorefractive crystals are typically used to produce phase conjugate correction at the output end of the fibre in double-pass schemes [1–6] or as mutually pumped phase conjugators in more recently reported single-pass geometries [7]. Double-pass correction schemes vary in their approach to overcome the apparent problem that only one (the e-polarised) polarisation state of the scrambled output from the fibre can undergo phase conjugate correction.

In the first demonstration of modal dispersion correction in a multimode fibre, using conventional four-wave mixing in $BaTiO_3$, it was shown that faithful reconstruction can indeed occur despite the apparent loss of polarisation information [1]. The authors speculated that as the information content of each polarisation component was assumed to be similar, conjugation of one component only was sufficient to ensure phase conjugate fidelity. Later work specifically addressed this

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problem using self-pumped phase conjugation to correct for waves having an arbitrary polarisation state. The input light was first decomposed into its two orthogonally polarised states, followed by rotation of the o-polarised component to become e-polarised, with subsequent phase conjugation on the two separate correctly polarised input beams [2]. Such a polarisation-preserving phase conjugator (PPPC) removes the perceived limitations imposed by polarisation scrambling through multimode fibres.

Subsequent experimental work [3] and theoretical analysis [4] explains these initially surprising results concerning the ability of a non-polarisation preserving phase conjugator (NPPPC) to correct for such polarisation scrambling in multimode fibres. Further work examined the quantitative differences between NPPPC and PPPC, and concluded that high contrast image restoration was only possible via PPPC [5], NPPPC resulting in contrast degradation, and reduced image resolution [6].

More recent work has examined the case of partial phase conjugation in which only a fraction of the input light was sent to the phase conjugator after transmission through a relatively long length (50 m) of multimode fibre of diameter 100 μm [8]. These interesting results serve as a basis for our study which further examines some of their important observations. In particular, we are engaged in exploiting pumped doped silica multimode fibres as gain-grating holographic resonators in direct analogy to the gain-grating resonators in bulk laser media [9]. The use of polarisation scrambling multimode fibres precludes the use of polarisation-based non-reciprocal transmission elements (NRTE) such as Faraday isolators that have been used so far to ensure efficient resonator operation. In this work we discuss such a fibre-based NRTE which offers an immediate solution to this problem.

We report here the results of our study on implementation of phase conjugate correction of modal distortion in highly multimode, (300 μm diameter), short (∼1 m) passive optical fibres. These fibre parameters are similar to those that we will dope with Nd and Yb for use in gain-grating fibre resonators. It is worth noting that both the length and the diameter of these fibres are important parameters, as dopant concentration and power handling determines the ultimate applicability of this fibre-based approach. Using the NPPPC scheme, we have examined the fidelity of phase conjugation for selected regions within the output from the multimode fibre, including severely off-axis modes. We have also studied the transmission for backward travelling light following phase conjugation to investigate the potential of our technique as a non-reciprocal transmission device in pumped active multimode fibres. To the best of our knowledge, there have been no other reports on phase conjugate correction in pumped multimode optical fibres, other than our earlier work in Tm:ZBLAN fibre, which used both PPPC and NPPPC techniques via a self-pumped $BaTiO_3$ crystal [10]. Although ideally an adaptive fibre resonator should rely on gain saturation rather than photorefraction, which is limited in response time and wavelength capability, for phase conjugate correction, the non-reciprocal transmission technique shown in the work presented here should be immediately implementable in any such gain-grating resonator geometry.

2. NPPPC with single and dual input beams

Fig. 1 shows the experimental set-up used to demonstrate phase conjugate correction of modal distortion in the highly multimode fibre. The 1.35 W 514.5 nm wavelength vertically polarised input beam originated from an Ar ion laser. This wavelength was chosen to achieve the optimum performance (response time and efficiency) for self-pumped phase conjugation from this $BaTiO_3$ crystal. Phase conjugate output was measured via the tilted glass wedge at the input end to the fibre. The fibre was ∼1 m in length, with a 300 μm core and an NA of 0.31. The light exiting the fibre was modally and polarisation scrambled, and was collimated by a ×6.3 microscope objective lens. An aperture placed directly after this lens enabled selection of either the whole beam, or on-axis/off-axis spatially restricted components for subsequent focussing into the $BaTiO_3$ self-pumped phase

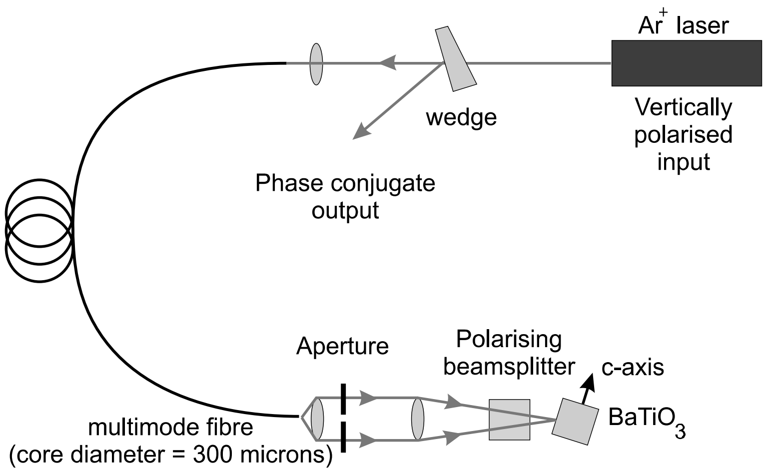

Fig. 1. Schematic of set-up used to investigate phase conjugate correction of modal distortion in a passive multimode fibre.

conjugator, via the polarising beam splitter. Any vertically polarised (o-polarised) light was reflected by the polariser, and sent into a beam stop.

Aperture sizes were set at either 7 mm (full size of the collimated output beam), 3 mm both on- and off-axis, and finally 2 mm on-axis. Smaller aperture sizes could not be investigated due to the unacceptably long build-up time of the phase conjugator at such low power levels. Following phase conjugation, the e-polarised component was relaunched into the fibre, and travelled back to the input end of the fibre. The part reflected from the wedge could then be measured or displayed via a CCD camera on a beam profiler. As discussed in detail in Ref. [5], the light retracing its path through the fibre is converted into two parts: a phase conjugate component which shows spatial and polarisation correction fidelity, and a non-phase conjugate background multimode output distributed among all spatial and polarisation modes of the fibre. Measurements of the power ratio between components polarised parallel to, or perpendicular to the input beam yielded a value of 3:1, which is consistent with the theoretical values reported in Ref. [5].

Fig. 2 shows the spatial profiles at input and output ends of the fibre. Fig. 2(a) was recorded at a distance of 10 mm from the output end of the fibre, and shows the highly multimode unpolarised output. Fig. 2(b)–(e) shows the phase conjugate reconstruction of the Gaussian input beam, reflected off the wedge, at a distance of 1 m from the fibre input end. With no aperture present, Fig. 2(b), the fidelity appears very good, whereas with the on-axis 3 mm aperture, Fig. 2(c), or on-axis 2 mm aperture, Fig. 2(d), the fidelity is seen to degrade, while the background noise increases. This is to be expected from both intuitive reasoning and also the results reported in Ref. [5]. With NPPPC only one half of the light returns to the input as a phase conjugate. The remaining half appears as background noise as seen most clearly in Fig. 2(d). As the aperture is progressively reduced, the assumption that the fidelity is independent of both the number of modes conjugated and also the fraction of the energy content of any individual mode inevitably breaks down. The extreme case would be phase conjugation of just one point in the multimode output beam (one lobe from a single high order mode). The information content in this case would be completely insufficient to permit any degree of phase conjugate fidelity. As more modal content is included in the phase conjugation process, the ratio of power in the phase conjugate to power in the non-phase conjugate noise increases, becoming true phase conjugation only in the case of PPPC discussed earlier.

Fig. 2(e) shows the last picture in this sequence, which was taken with a 3 mm aperture, positioned 2 mm off-axis. The phase conjugate is again readily

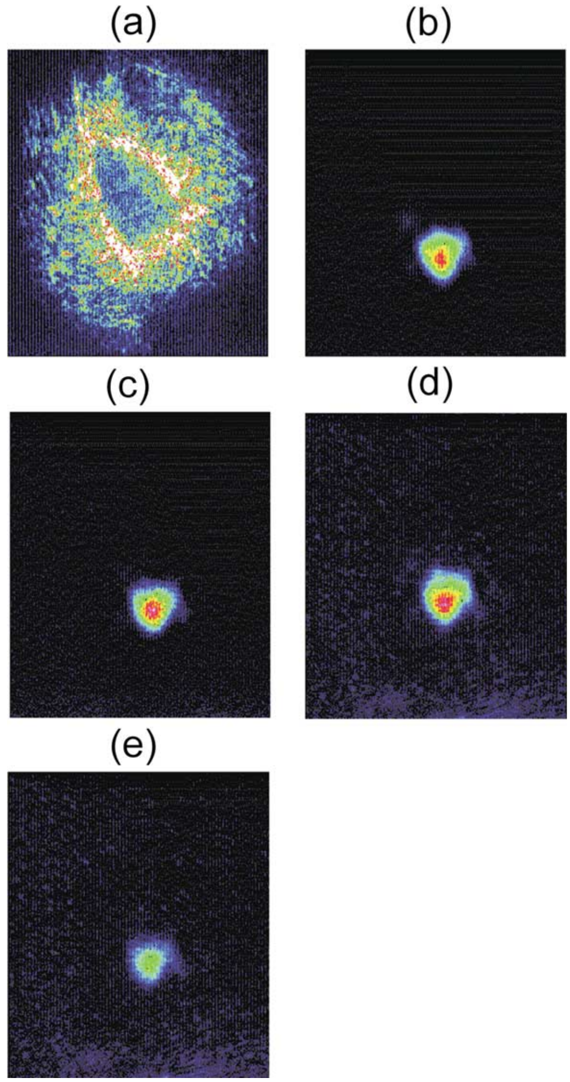

Fig. 2. Spatial output from the multimode fibre: (a) the single-pass output at the end of the fibre; (b–e) the phase conjugate output recorded at the input end of the fibre after double pass and modal correction after passing through an on-axis aperture of diameter 7 mm (b), 3 mm (c) and 2 mm (d); (e) the phase conjugate after passing through an aperture of diameter 3 mm, centred 2 mm off-axis.

visible, but the level of the background noise is higher than for the on-axis case shown in Fig. 2(c).

Fig. 3 shows the modified set-up that was implemented for two discrete Gaussian inputs. An additional beam splitter generated two roughly equal power inputs, which were phase conjugated via NPPPC as before. The additional points of interest here are twofold. Firstly, transiently blocking one input had no effect on the existing output (two separate phase conjugates) as the crystal response time exceeded the blocking time by more than an order of magnitude. Secondly, for future implementation of gain-grating techniques in pumped doped fibres, we needed to confirm that multiple inputs can be faithfully conjugated and remain spatially separated. Unlike the case for implementation of gain-grating phase conjugation in bulk laser crystals [9], where beams can overlap in the gain medium but remain spatially resolvable in the far-field through angular adjustment, the same degree of freedom does not exist in fibre geometry. Two input beams become irretrievably mixed as they propagate down the fibre, and only phase conjugation can reconstruct their initial spatial separation.

3. Non-reciprocal transmission characteristics

As stated earlier, there is a need to implement a non-reciprocal transmission element in all-fibre gain-grating resonator designs. Within the gain medium, optimised diffraction efficiency occurs for a large modulation depth in the interference pattern produced by overlap of the signal and pump beams. For high gain media this will not occur without large attenuation of the amplified input signal or amplified spontaneous emission beam that has been round the loop once, to become the forward pump beam. The phase conjugate nature of the backward travelling wave in the multimode fibre can be exploited to produce just such an NRTE.

Fig. 4 shows a modified version of the previous set-up, in which the fibre has been cut into two parts, A and B, and separated by a variable width gap, z, as shown in the inset. Fibre B can now be positioned to select specific regions from within the output modal content from fibre A, by variation of z, or adjustment of its lateral position. As z is increased, the forward transmission, $T(+)$, (defined as power out of fibre B as a ratio of the power sent into fibre A) in the non-phase conjugate direction decreases. With reference to Fig. 5, $T(+)$ is

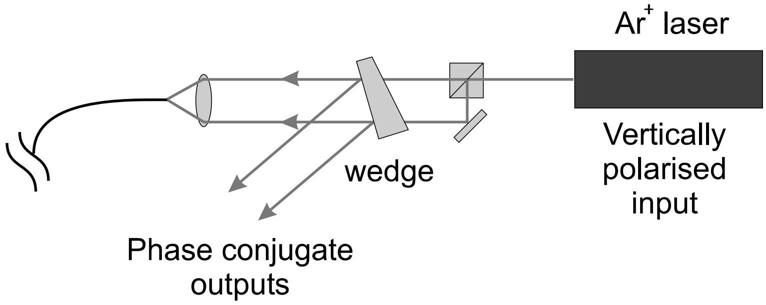

Fig. 3. Modification to Fig. 1 to allow two simultaneous input beams.

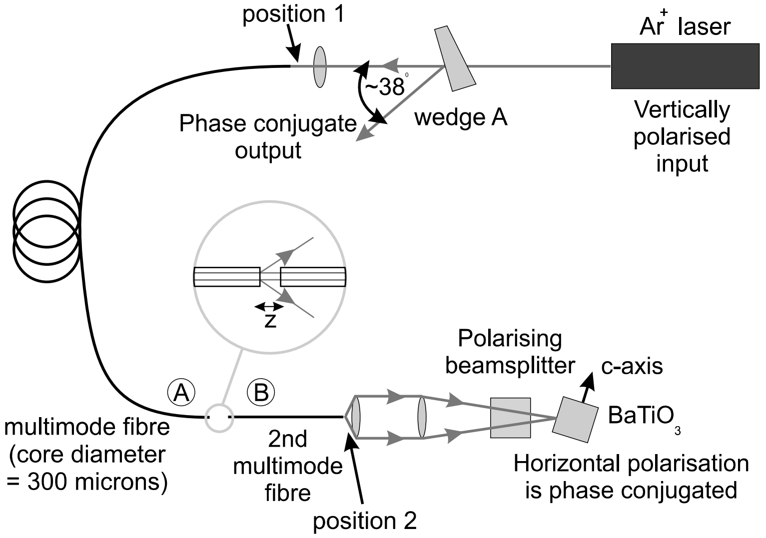

Fig. 4. Use of two separate multimode fibres to allow variation of modal content for subsequent phase conjugation.

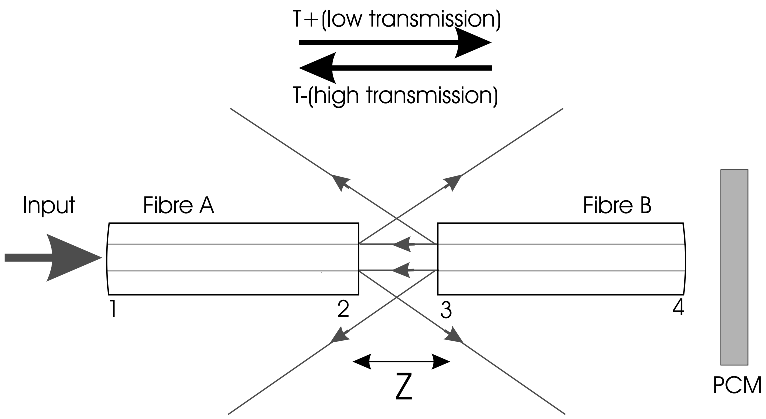

Fig. 5. Schematic of two fibre geometry separated by distance z, showing directions of low ($T(+)$) and high ($T(-)$) transmission. PCM: phase conjugate mirror.

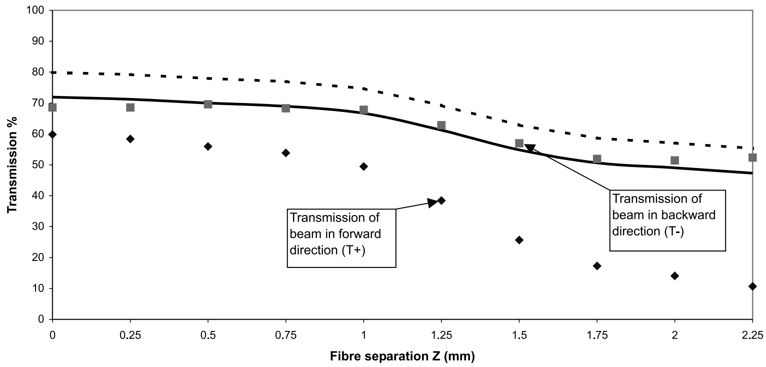

Fig. 6. Measured values for $T(+)$ and $T(-)$ as a function of separation, z.

therefore defined as power at point 4 divided by power at point 1. The transmission through the two fibre system in the backwards (phase conjugate) direction, $T(-)$, is similarly defined as the ratio of the power out of fibre A at its input end to that being relaunched by the phase conjugator at the output end of fibre B (ratio of power at point 1 to that at point 4).

These transmissions have been measured and are shown in Fig. 6, labelled as $T(+)$ and $T(-)$ respectively, plotted as a function of distance z. The forward and backward transmissions are clearly different: of most importance is their very different limiting values as z is progressively increased. In the forward direction the transmission is essentially given by, neglecting all other losses, the ratio of the acceptance area of the core of fibre B to the area that the light exiting fibre A has spread out to at a particular value of z. In the backwards direction however, the field consists of a phase conjugate part which will couple from fibre B back into fibre A, with a theoretical efficiency of 100% for any value of z, and a non-phase conjugate component which should have the same coupling characteristics exhibited by the forward travelling wave from point 2 to point 3. Given the measured values for $T(+)$ therefore, the values for $T(-)$ can be predicted by the empirical formula:

$$T(-) = \underbrace{\tfrac{1}{2}}_{\text{phase conjugate}} + \underbrace{\tfrac{1}{2}T(+)}_{\text{non-phase conjugate}} \qquad (1)$$

From Fig. 6 we can see that $T(-)$ does indeed approach its limiting value of 50% at values of z of $\sim$2 mm.

The power transmitted in the backward direction, $P(-)$, was measured knowing the reflectivity at wedge A. The power out of fibre A at position 1 could then be found by taking into account the reflectivity of the glass wedge and the transmission of the objective lens. The wedge was at an angle of $\sim 38^\circ$ and so had different reflectivities for vertical and horizontal output polarisation components. The measured vertical reflectivity, r_v, was 7.5% whilst the horizontal reflectivity, r_h, was 1.9%. The effective reflectivity of the wedge, r_{eff}, is therefore given by

$$r_{eff} = 7.5\left(\frac{V}{100}\right) + 1.9\left(\frac{H}{100}\right) \qquad (2)$$

where V and H are the percentage of the output field in the vertical and horizontal polarisations respectively. This had to be taken into account when measuring $P(-)$, since the ratio between the two orthogonal polarisations varied as the distance between the fibres, z, was increased. When $z = 0$ the phase conjugate reconstructed field is vertically polarised whilst the non-phase conjugate part is split equally between the vertical and horizontal polarisations. Therefore 75% of the field is vertically polarised and 25% horizontally polarised. As the distance, z, increases the percentage of the vertical polarised field in $P(-)$ increases, as less of the non-phase conjugate (unpolarised) part is transmitted across the gap between the two fibres.

The dashed line shown in Fig. 6 is an empirical fit based on Eq. (1), knowing the measured values for $T(+)$, which determines both the power launched into fibre B and the reciprocal relaunch of the non-phase conjugate part into fibre A. This empirical fit (dashed line) does not pass through the measured $T(-)$ data points because we are assuming an efficiency of 100% transmission of the phase conjugate part of the field. Experimentally, however, the percentage of the phase conjugate field that is transmitted through the two fibres is reduced due to absorption in the fibres and Fresnel losses at the fibre ends. This phase conjugate transmission value was varied until a best fit for the measured data points was obtained (unbroken line) and is given by

$$T(-) = \underbrace{0.42}_{\text{phase conjugate}} + \underbrace{\tfrac{1}{2}T(+)}_{\text{non-phase conjugate}} \quad (3)$$

Only 84% ($1/2 \times (84\%) = 42\%$) of the phase conjugate part is therefore transmitted in the backward direction rather than the theoretically predicted 100%. It is not possible to test the intriguing possibility of increasing the value of z to arbitrarily large values, as the power launched into fibre B (via $T(+)$), which generates the self-pumped phase conjugate signal, falls below the few mW threshold value required.

One other point to note is that when the distance between the fibres, z, is nominally zero the transmission in the forward and backward directions shown in Fig. 6 is different. This is a consequence of the fact that even with the fibres in close contact the non-phase conjugate light can never achieve a 100% coupling efficiency between the two fibres. In the backwards direction however, the phase conjugate part of the field has a higher coupling efficiency making the overall transmission in this direction higher. Only when we have 100% transmission in the forward direction will the values of $T(+)$ and $T(-)$ agree at $z = 0$.

This two fibre system is also very insensitive to lateral misalignment. The same set-up was used as in Fig. 4, and the axial separation z was set to $\sim$100 μm. The lateral displacement of the fibres, y, was then varied and the reconstructed output of the system recorded. Fig. 7 shows the phase conjugate output at the input end of the system for various values of displacement, y.

From the above results and discussion, it is clear we can successfully construct an NRTE element. The present values of contrast ratio, $T(-)/T(+)$, are only of order 5, but in principle there is no theoretical limit to increasing this value. In the present implementation, the power levels required to achieve self-pumping for the $BaTiO_3$ are of order a few mW, and this effective threshold limits the values of z possible via $T(+)$. In our future gain-grating work, such limitations however should not apply.

4. Implementation of NRTE in fibre gain-grating resonators

Fig. 8 shows the intended scheme for NRTE use in an all-fibre gain-grating resonator. Such resonators routinely require a substantial reduction of the power in the forward propagating beam to compensate for the large round-trip gain. This ensures that the grating that is written in the gain medium has large modulation depth. The backward propagating beam however needs to experience significant overall gain around the loop, and so similar attenuation is not desirable. Additionally, the fibre needs to be pumped through the same focussing optics as used for the initial injected signal, so deliberate misalignment of the fibre carrying the forward propagating beam is unavoidable.

The inset in Fig. 8 shows the schematic diagram of the set-up to be implemented. Exact details for positional offsets will depend on the optics used (NA values, focal length, and physical dimensions). This scheme can prove very useful, given that an equivalent Faraday isolator or NRTE cannot be used for polarisation scrambling multimode fibres. Work is currently underway on a fibre-based resonator and these results will be published elsewhere.

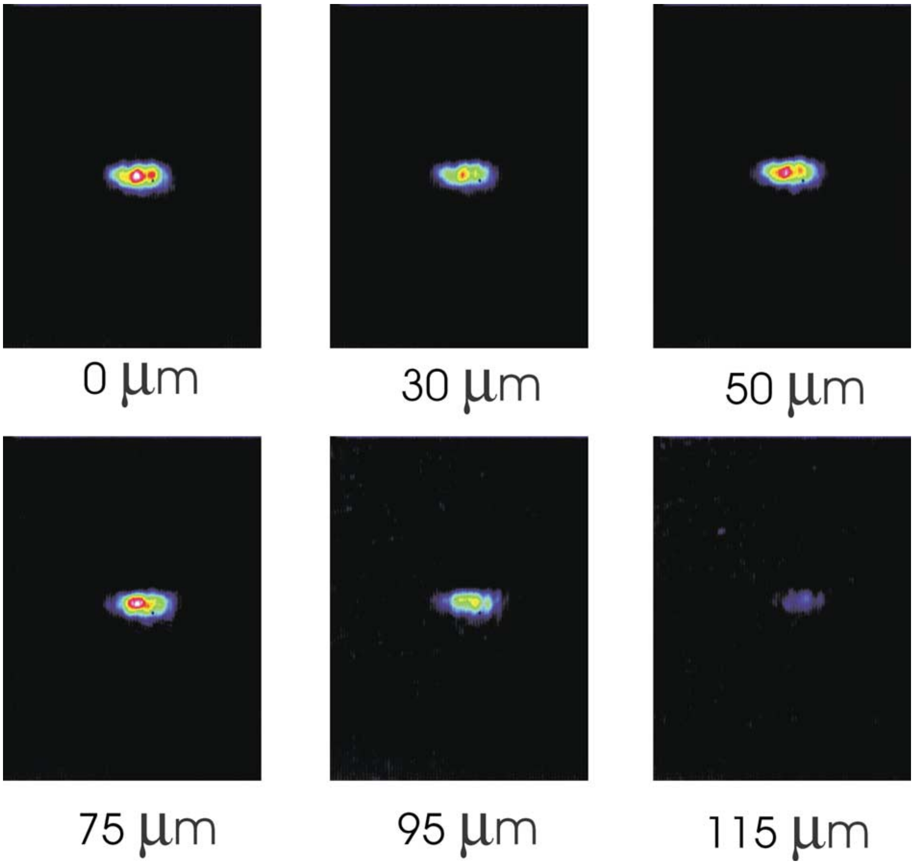

Fig. 7. Phase conjugate output for lateral misalignment between the two fibres.

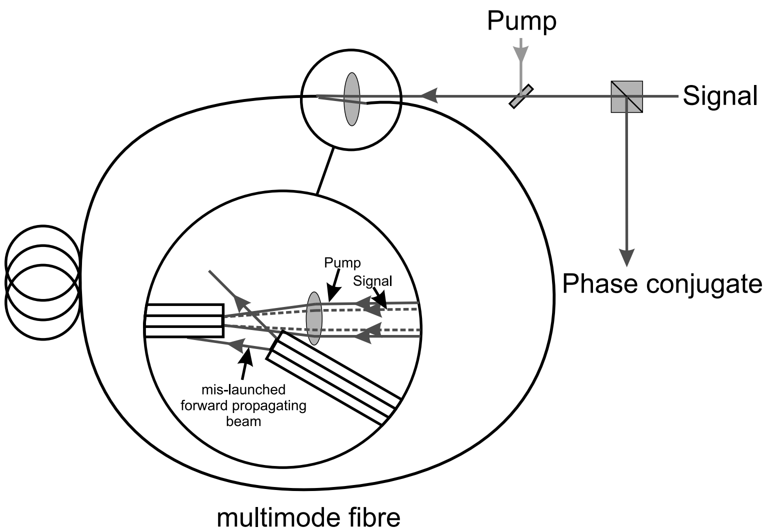

Fig. 8. Schematic showing implementation of NRTE in gain-grating fibre resonator geometry.

5. Conclusions

In conclusion we have shown that correction for polarisation and modal scrambling within a passive highly multimode fibre can occur in a non-polarisation preserving phase conjugate arrangement scheme for a large degree of both on-axis and off-axis undersampling of the total multimode output. Utilising the properties of phase conjugation, we have further demonstrated a useful non-reciprocal transmission device that will have immediate application in gain-grating resonators that use multimode fibres as the gain medium. A contrast ratio for the NRTE of a factor ~5 has been shown using self-pumped photorefractive phase conjugation, and this should improve dramatically once phase conjugation via gain saturation is implemented in the fibre.

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