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We propose a beam cleanup setup to convert a multimode beam into a single-mode beam by use of the Brillouin effect in a multimode gradient-index (GI) fiber. Phase conjugation and beam cleanup regimes in highly multimode fibers are discussed, and the self-aligned GI fiber Brillouin cavity is presented. We report a preliminary conversion from an $M^2=6.5$ beam into an $M^2=1.3$ beam with 31% efficiency. © 2006 Optical Society of America

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The increase in fiber laser and amplifier output power is limited by nonlinear effects and material damage due to the high power density, especially in pulsed operation. Output powers of several hundreds watts have recently been achieved in large-mode-area quasi-single-mode fibers. To further increase the core diameter, an alternative approach consists in correcting the beam profile after a multimode fiber amplifier by a nonlinear beam cleanup method. This technique has been demonstrated by self-referencing two-wave mixing.[1] In this Letter we propose to accomplish beam cleanup by using the Brillouin effect in a multimode fiber. We demonstrate efficient and highly stable beam cleanup in a multimode gradient-index (GI) fiber by using a self-aligned loop geometry.

Stimulated Brillouin scattering in multimode fibers can lead to phase conjugation as reported in pulsed operation,[2] cw operation,[3] and with a loop.[4] It can also lead to beam cleanup as observed by Bruesselbach[5] in 1993. To show that those two behaviors are linked to the fiber geometry, we calculate the Brillouin gain associated with each fiber mode in both GI and step-index (SI) fibers.

The scalar nonlinear polarization density for the Brillouin effect under the flat Brillouin gain approximation is[6,7]

$$\mathcal{P}_{\mathrm{NL}}=\frac{3}{2}\epsilon_0\chi^{(3)}E_pE_p^*E_s(x,y,z,t), \tag{1}$$

with ϵ_0 the vacuum permittivity and $\chi^{(3)}$ the third-order nonlinearity coefficient for the Brillouin effect. $\chi^{(3)}$ is proportional to the commonly used Brillouin gain g_B. E_s and E_p are the scalar electric fields for the Stokes and the pump waves, respectively. Now consider a waveguide that can carry N modes with electric field distributions $\psi_1(x,y)\ldots\psi_N(x,y)$ and propagation constants $\beta_1\ldots\beta_N$. The pump and Stokes electric fields are similarly decomposed:

$$E_{s,p}(x,y,z,t)=\sum_{i=1}^{N}c_i^{s,p}(z,t)\psi_i(x,y)\exp[i(\pm\beta_i^{s,p}z-\omega_{s,p}t)], \tag{2}$$

where the complex mode coefficients $c_i^s(z,t)$ and $c_i^p(z,t)$ can vary along the fiber or in time. ω_s and ω_p are the Stokes and pump waves frequencies. The sign in front of β is + for the pump wave and − for the Stokes wave. In the following we consider the hypothesis of a scalar field (no depolarization in the guide), no absorption, no mode mixing, and cw operation (c_i^s depends only on z). Then the injection of Eqs. (1) and (2) into the well-known Maxwell propagation equations[6] leads to the following evolution equation for each Stokes mode:

$$\frac{\mathrm{d}c_n^s(z)}{\mathrm{d}z}=\alpha g_B\sum_{i,j,m}R_{ijmn}c_i^pc_j^{*p}c_m^s(z)\exp(i\Delta\beta_{ijmn}z), \tag{3}$$

where α is a constant, R_{ijmn} is an overlapping factor, and $\Delta\beta_{ijmn}$ is a phase mismatch factor defined by Eqs. (4) and (5). After integration along the fiber, only the terms with $\Delta\beta_{ijmn}=0$ do not vanish:

$$R_{ijmn}=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\psi_i\psi_j^*\psi_m\psi_n^*(x,y)\mathrm{d}x\mathrm{d}y, \tag{4}$$

$$\Delta\beta_{ijmn}=\beta_i^p-\beta_j^p-\beta_m^s+\beta_n^s. \tag{5}$$

A full resolution of Eq. (3) is possible at the Brillouin threshold for any given set of c_i^p. In the case of highly multimode fibers, it leads to good-quality phase conjugation in short SI fibers (limited to several meters by the Brillouin frequency shift[7]) and to poor-quality phase conjugation in GI fibers. Our experimental investigations in SI 50 μm and GI 62.5 μm core diameter highly multimode fibers have confirmed good-quality phase conjugation in the short (2 m) SI fiber, no phase conjugation or beam

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cleanup in the long (1 km) SI fiber, bad-quality phase conjugation in the short (2 m) GI fiber, and beam cleanup in the long (>30 m) GI fiber. This behavior difference between GI and SI fibers comes from the mode overlap between pump and Stokes fiber modes. In the case of SI fibers, the mode overlap factor R_{ijmn} is similar for all Stokes modes, thus enabling phase conjugation, whereas in GI fibers this factor is higher for the lower-order Stokes mode, leading to a favored reflection of lower-order modes.

Let us try to understand where those behaviors come from. If phase conjugation occurs, the Stokes wave is the phase-conjugated replica of the pump wave, i.e., $c_i^s(0)=c_i^{p*}(0)$. Under the additional simplifying hypothesis of uniform depletion and amplification profiles [we can write $c_n^s(z)=c_n^s(0)f_s(z)$ and $c_n^p(z)=c_n^p(0)f_p(z)$ with repartition functions f_s and f_p independent of n] and no propagation constant degeneration (only terms with $m=n, i=j$ or $m=i, j=n$ satisfy $\Delta\beta_{ijmn}=0$), Eq. (3) leads to the power evolution equation:

$$\frac{\mathrm{d}P_n^s}{\mathrm{d}z} = -\left(2g_B\sum_i R_{in}P_i^p - g_B R_{nn}P_n^p\right)P_n^s, \qquad (6)$$

with $R_{in}=R_{iinn}=R_{inin}$, $R_{nn}=R_{nnnn}$, and P_n^s and P_m^p the powers contained, respectively, in the nth Stokes mode and the mth pump mode. The power carried by each mode is $P_n(z,t)=(nc\epsilon_0/2)|c_n(z,t)|^2$. Now in the case of beam cleanup, the Stokes wave is contained in a single fiber mode n and $P_m^s=0$ for $m\neq n$. The power evolution equation (6) is changed into

$$\frac{\mathrm{d}P_n^s}{\mathrm{d}z} = -\left(g_B\sum_i R_{in}P_i^p\right)P_n^s. \qquad (7)$$

.

The terms in parentheses in Eqs. (6) and (7) represent the linear Brillouin gain of the Stokes mode $P_n^s(z)$ and are plotted in arbitrary units at threshold in Fig. 1 for uniform repartition of pump power on fiber modes [$P_n^p(0)=P^p(0)$]. On the one hand, good-quality phase conjugation requires the same uniform repartition of Stokes power on fiber modes [$P_n^s(0)=P^s(0)$]. This condition is fulfilled in the SI fiber: the various Stokes modes experience the same linear gain, which enables high-equality phase conjugation.

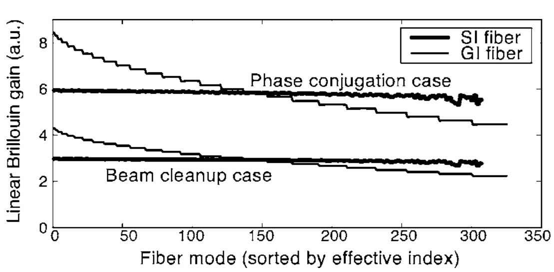

Fig. 1. Linear gain for each Stokes fiber mode sorted by propagation constants (lower-order modes at the left). The calculation is done for uniform excitation of the pump modes and for two fiber geometries: a SI fiber (normalized frequency $V=35$) and a GI fiber ($V=52$).

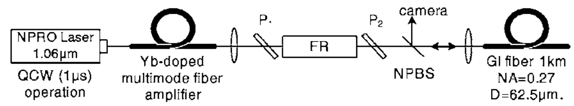

Fig. 2. Experimental setup.

The condition is not fulfilled in the GI fiber, where the linear gain for the lower-order modes is nearly twice as large as for the higher-order modes: the hypothesis of phase conjugation must be rejected in the GI fiber. On the other hand, beam cleanup requires selection of a particular mode. The favored reflection of lower-order modes in GI fibers leads to beam cleanup. In SI fibers there is no mode selection and so no beam cleanup.

In summary, we draw the following conclusions for highly multimode fibers: good-quality phase conjugation can be expected in short[7] SI fibers but not in GI fibers. Beam cleanup can be expected in GI fibers but not in SI fibers.

Experimental investigations of the Brillouin effect in a GI fiber have been carried out with the setup shown in Fig. 2. A very large core Yb-doped multimode fiber amplifier is seeded by a quasi-cw (Qcw) single-frequency laser (1 μs pulses at 33 kHz). The amplified beam is depolarized and has the shape shown in Fig. 3(a) (beam parameter $M^2=6.5$). Its horizontal polarization has a peak power limited to 150 W and is coupled in a 1 km long GI fiber with an aperture of NA=0.27 and a core diameter of $d=62.5\ \mu$m($V=52$). The reflected beam is observed after the nonpolarizing beam splitter.

We observed that the Stokes beam is usually reflected as an LP_{11} mode as shown in Fig. 3(b), independently of the pump coupling conditions. The reason is that the LP_{11} mode has a more balanced overlap with all pump modes: above threshold, pump depletion is more uniform and the LP_{11} mode gain becomes higher than the LP_{01} mode. Nevertheless, it has been possible to select the fundamental LP_{01} fiber mode with a very careful coupling of the pump beam into the lowest-order fiber modes: we then obtained a Brillouin reflectivity of 45% of the 115 W incident pump peak power in the GI fiber with a measured $M^2=1.2$. However, selection of the LP_{01} fiber mode is difficult to obtain because LP_{11} is fundamentally favored.

To impose the LP_{01} mode to be reflected with stable operation, an external selection is required. We propose to decrease the Brillouin threshold of the LP_{01} mode by injecting part of the Stokes beam at the fiber end into the LP_{01} mode only. The Brillouin cavity is then closed for the fundamental mode and opened for higher-order modes. This design requires, on the one hand, the conservation of the fundamental mode in the fiber and, on the other hand, a filter with very good rejection of the higher-order mode, especially the LP_{11} modes.

Those two conditions are realized in our setup displayed in Fig. 4. The amplified pump pulse is coupled into the 30 m long GI multimode fiber with a core diameter of 62.5 μm and a normalized frequency $V=52$ (325 modes on each polarization). We have observed that under careful coupling of the LP_{01} mode only, this 30 m multimode GI fiber can propagate the fundamental mode without mode mixing or depolarization. The fundamental mode filtering is made with a single-mode fiber that is spliced to the multimode GI fiber. This 1.5 m fiber provides a complete rejection of the high-order modes.

Thus only the horizontally polarized fundamental mode of the multimode GI fiber sees a closed cavity: its Brillouin threshold power is lowered and it is preferably reflected. Note that the sensitive alignment of the two fiber cores is precisely provided by the splicing.

The reason that the loop decreases the Brillouin threshold is the following. It is usually admitted that the pump power threshold P_p^{th} for the Brillouin effect without the cavity effect in fibers is defined by the empirical condition $g_B P_p^{\mathrm{th}} L/S = 21$, where g_B is the Brillouin gain coefficient, S is the core surface, and L is the fiber length when absorption is negligible. At that pump power, the total Brillouin gain $G_B = \exp(g_B P_p^{\mathrm{th}} L/S) = \exp(21) \approx 1.3 \times 10^9$ is then large enough to initiate the effect with spontaneously emitted photons at the fiber end. In the case of the Brillouin cavity, the threshold condition is reached as soon as the coupling losses are compensated by the Brillouin gain: $G_B = 1/r$, where r is the ratio of Stokes power that is injected in the single-mode fiber. The condition rewrites $g_B P_p^{\mathrm{th}} L/S = -\ln(r)$. The power threshold is then decreased by a factor $\eta = -\ln(r)/21$. η is plotted in Fig. 5 as a function of coupling coefficient r for the cases of cw regime and Qcw with three passes in the GI fiber. The spontaneous Brillouin emission is taken into account and is responsible for threshold at a low coupling coefficient of $r < 10^{-8}$. At higher coupling, the new condition implies a power threshold decrease of a factor of 3 to 5.

In the experimental setup, the coupling coefficient is $r \approx 0.2$ in the Qcw regime. Power thresholds are $P_p^{\mathrm{th}} = 39$ W with an open cavity and $P_p^{\mathrm{th}} = 21$ W with a closed cavity. The decrease factor 0.54 is not far from the expected value 0.40. The maximum intracavity Brillouin reflectivity was 31% at 150 W of incident pump peak power in this preliminary experiment. The beam shapes of the incident pump beam and the reflected Stokes beam are shown in Fig. 6. The Stokes beam is linearly polarized and its beam quality is $M^2 = 1.3$. It is very stable and the cavity is easy to set, thanks to the precise alignment done by the splicing.

Fig. 3. Beam shapes: (a) incident pump beam; (b) reflected Stokes beam (LP_{11} mode).

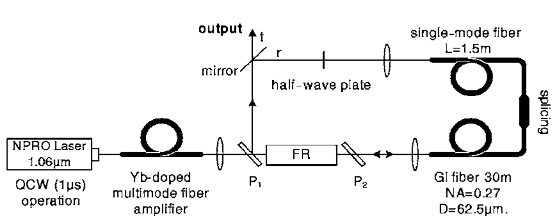

Fig. 4. Self-aligned Brillouin cavity for beam cleanup. FR, Faraday rotator; P_1, P_2, polarizing beam splitters.

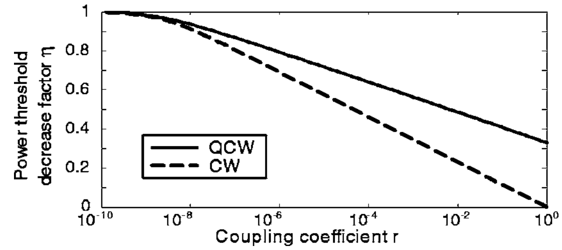

Fig. 5. Power threshold decrease in a closed Brillouin cavity relative to the open Brillouin cavity as a function of the coupling coefficient r for cw and Qcw operation.

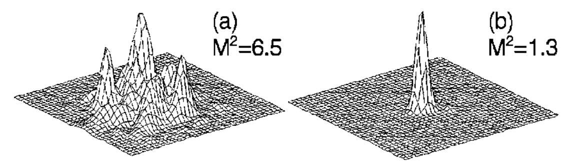

Fig. 6. (a) Pump beam shape emitted by the multimode fiber amplifier and (b) Stokes beam shapes in the far field.

In conclusion, we have demonstrated a Brillouin cavity setup with self-alignment capacity using a standard gradient-index multimode fiber for beam cleanup of high-power output of a multimode fiber amplifier. An intracavity conversion efficiency of 31% in the fundamental mode has been obtained. Higher efficiency is expected in cw operation because of the lower threshold. Further developments will include extracting the Stokes power from the cavity and recycling the vertical pump polarization. This nonlinear mode converter based on beam cleanup in a multimode GI fiber should be able to convert any coherent multimode depolarized beam into a single-spatial-mode linearly polarized beam with good efficiency.

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