Air Force Institute of Technology

AFIT Scholar

2007

Use of a Continuous Wave Raman Fiber Laser in Graded-index Multimode Fiber for SRS Beam Combination

Nathan B. Terry

Kevin T. Engel

Thomas G. Alley

Timothy H. Russell

Use of a continuous wave Raman fiber laser in graded-index multimode fiber for SRS beam combination

Nathan B. Terry, Kevin T. Engel, Thomas G. Alley, and Timothy H. Russell

Department of Engineering Physics, Air Force Institute of Technology
2950 Hobson Way, AFIT/ENP, Wright-Patterson Air Force Base, OH 45433
thomas.alley@afit.edu
http://www.afit.edu/en/ENP

Abstract: We report using a Raman fiber laser (RFL) based on a multimode graded-index fiber as a novel method for beam combination of two continuous wave pump beams. Due to stimulated Raman scattering, the RFL generates a Stokes beam which can be up to 300% brighter than the pump beams. Up to 5.8 W of Stokes power is generated with an optical conversion efficiency of 56%.

References and links

1. T.Y. Fan, "Laser beam combining for high-power, high-radiance sources," IEEE J. Sel. Top. Quantum Electron. **11**, 567-577 (2005).
2. T.H. Russell, W.B. Roh, and J.R. Marciante, **"**Incoherent beam combining using stimulated Brillouin scattering in multimode fibers," Opt. Express **8**, 246-254 (2001).
3. B.G. Grime, W.B. Roh, and T.G. Alley, "Phasing of a two-channel continuous-wave master oscillator-power amplifier by use of a fiber phase-conjugate mirror," Opt. Lett. **30**, 2415-2417 (2005)
4. M.H. Smith, D.W. Trainor, and C. Duzy, "Shallow angle beam combining using a broad-band XeF laser," IEEE J. Quantum Electron. **26**, 942-949 (1990).
5. C.A. Codemard, P. Dupriez, Y. Jeong, J.K. Sahu, M. Ibsen, and J. Nilsson, "High-power continuous-wave cladding-pumped Raman fiber laser," Opt. Lett. **31**, 2290-2292 (2006).
6. B.M. Flusche, T.G. Alley, T.H. Russell, and W.B. Roh, "Multi-port beam combination and cleanup in large multimode fiber using stimulated Raman scattering," Opt. Express **14**, 11748-11755 (2006).
7. L. Lombard, A. Brignon, J.P. Huignard, E. Lallier and P. Georges, "Beam cleanup in a self-aligned gradient-index Brillouin cavity for high-power multimode fiber amplifiers," Opt. Lett. **31**, 158-160 (2006).
8. K.S. Chaing, "Stimulated Raman scattering in a multimode optical fiber: evolution of modes in Stokes waves," Opt. Lett. **17**, 352-354 (1992).
9. T.H. Russell, S.M. Willis, M.B. Crookston and W.B. Roh, "Stimulated Raman scattering in multimode fibers and its application to beam cleanup and combining," J. Nonlinear Opt. Mater. **11**, 303-316 (2002).
10. S. H. Baek and W. B. Roh, "Single-Mode Raman fiber laser based on a mulitmode fiber," Opt. Lett. **29**, 153-155 (2004).
11. W. Yumming, D. Jingcao, Z. Mingde, and S. Xiaohan, "Theoretical and experimental study on multimode optical fiber grating," Opt. Commun. **250**, 54-62 (2005).

1. Introduction

Much effort has been devoted to finding and investigating methods of combining semiconductor lasers, fiber lasers and solid state lasers to produce efficient high-average-power systems with bright output in a combined single beam.[1] Coherent beam combination combines elements at the same wavelength by employing some mechanism for controlling the phases of the various elements. Wavelength (or spectral) beam combination utilizes a diffractive optic to combine elements operating at different wavelengths into a single beam with broad spectral output. Another approach that is not easily classified in either of these

two categories is that of beam combination via nonlinear optical processes. Stimulated Brillioun scattering (SBS) has been used to achieve beam combination in bulk media [1] and in fibers [2,3]. Stimulated Raman scattering (SRS) has also been used for beam combination in bulk media, producing single output beam. The spectral content of this beam consists of multiple Stokes orders [4]. SRS as a beam combination and power scaling method remains largely undeveloped, owing in part to the difficulty of achieving a low Stokes threshold.

One way to achieve a low Stokes threshold for SRS is to use an optical fiber oscillator (Raman fiber laser or RFL) with a singlemode core as the nonlinear beam combination medium. A single clad, singlemode core fiber requires a singlemode pump source and can preclude the use of a multimode pump source or multiple pump sources due to inefficient pump coupling, eliminating the utility of the device. Codemard *et al* recently used a double clad fiber to allow multimode pumping in a Raman fiber laser while taking advantage of low threshold in a singlemode core [5]. Beam combination and the use of multiple pump sources were not investigated; pumping was achieved through use of a multimode MOPA. The use of a singlemode core ensured a diffraction limited output beam.

The use of a singlemode core may not be desirous if power scaling is a goal. The Stokes power in a singlemode core will be more restricted relative to a multimode core due to optical damage limits. On the other hand, a multimode fiber core allows efficient coupling of multimode pump sources. It is therefore of interest to examine SRS beam combiners based on using an RFL in a multimode fiber. Recent experiments in our labs involving SRS beam combination have used high peak powers from temporally coherent pulsed pump laser beams in multimode fiber to reach Stokes threshold [6]. In this paper, we demonstrate that beam combination using an RFL avoids a high Stokes threshold while also demonstrating that SRS beam combination can be achieved using continuous-wave (CW) incoherent pump sources.

In general, it is possible to achieve enhanced beam quality in the Raman output without using a double clad fiber with singlemode core. Instead, enhanced beam quality can be achieved through the process of beam cleanup. Observations of SRS in graded index multimode fibers have shown that a Stokes beam possesses better beam quality than the pump beam which generated it, an effect known as beam cleanup. Both SBS and SRS can produce beam cleanup [6-9], as can an RFL [10]. Beam cleanup occurs when the fundamental mode of the emerging Stokes beam experiences preferential amplification relative to neighboring transverse modes of the fiber. The degree of beam cleanup experienced by the Stokes beam is highly sensitive to the overlap of the pump beam with the lower-order modes of the fiber [8]. Due to beam cleanup, a multimode fiber can produce beam quality nearly comparable to that of a singlemode fiber, with an M^2 greater than or equal to 1.3 [6,7,10].

This paper reports the first SRS beam combination of two CW temporally incoherent pump sources using an RFL based on a multimode graded-index fiber. Employing an oscillator avoids the high Raman power thresholds of previous experiments and thus allows the use of CW pump sources. This demonstrates a novel technique for SRS beam combination of CW pump sources. This technique produces a Stokes beam which is up to 3 times brighter than the pump beams. It can provide up to 5.8 W of Stokes power with an optical conversion efficiency of 55%, which is to our knowledge, the highest optical conversion efficiency of any multimode pumped RFL. This technique also produces slope efficiencies which approach or even exceed unity at the powers tested.

2. Experimental

The setup of this experiment is shown in Fig. 1. The multimode fiber used in this experiment was a graded-index germano-silicate fiber with 50 μm diameter core (0.20 NA) and a 125 μm diameter cladding. Two separate unpolarized Nd:YAG pump lasers (1064 nm) were first polarized in orthogonal directions using polarizing beam splitters (PBS). Each polarized pump beam (channel) then traversed a λ/2 waveplate before being combined into a single beam by passing each channel through a common PBS. Rotating the respective waveplates changed the amount of pump power from each laser that was launched into the gain fiber; rotating the waveplate did not alter the launching conditions of either pump beam. The output

from the RFL was likewise collimated using a microscope objective. The pump beam was separated from the Stokes beam using a long wave pass edge filter at 1064nm.
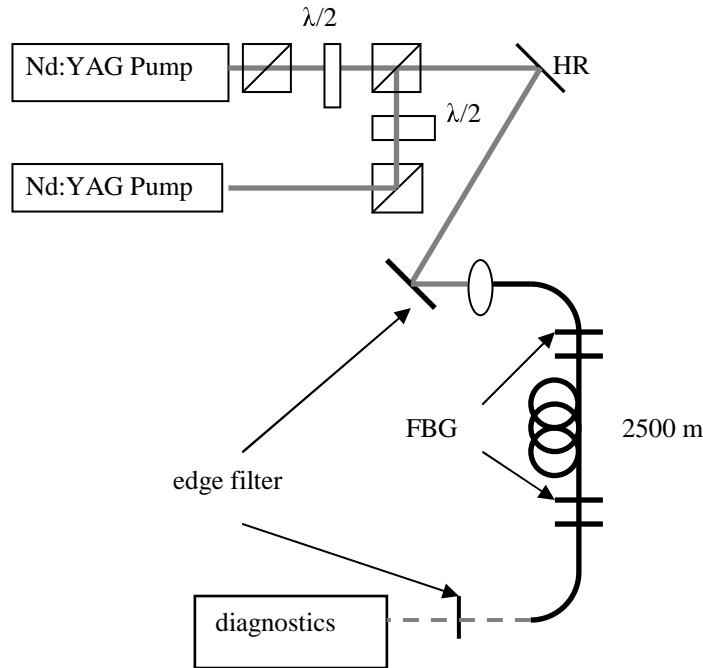

Fig. 1. Schematic diagram of experimental setup.

The high reflectivity (HR) fiber Bragg grating (FBG) on the input end of the cavity possessed a single-mode reflectivity of 99% at the first Stokes wavelength (1117 nm) as given by the manufacturer. The low-order mode reflectivity spectrum of this grating, as measured by us, is shown in Fig. 2. FBGs written to multimode fibers have the property that each mode of the fiber is associated with a unique wavelength corresponding to modal variation of the Bragg condition and a specific reflectivity, which may or may not be the same as the reflectivity for other modes [11]. In our data we observed a nominal 0.3 to 0.4 nm spacing between modes. Each of the 5 RFL configurations tested used the same HR FBG while the output FBG was varied. The peak single-mode reflectivity of the 5 output coupler FBGs used in this experiment as given by the manufacturer were respectively 99%, 90%, 80%, 60%, and 30% at the first Stokes wavelength (1117 nm). The Fresnel reflection off of a bare fiber end was also used as an output coupler with a reflectivity of 4%. In each configuration, the input end of the fiber was aligned to maximize the Stokes power produced; the RFL was then characterized in terms of power, beam quality and spectral content. A total of 6 different RFL beam combiner configurations were investigated.
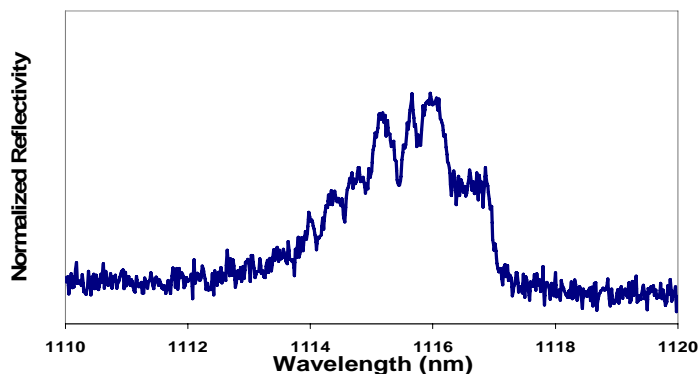
Fig. 2. Normalized reflectivity spectrum of the FBG on the front end of the RFL.

3. Results and analysis

The power in the Stokes beam was measured as a function of the pump power coupled into the gain fiber. Initially the RFL was pumped with only a single pump channel. Once the power in the first pump channel reached its maximum power of about 5 W, additional pump power was added via the second channel. The generated Stokes powers were independent of which channel was used for the initial pumping. The Stokes power generated by a RFL using a 90% FBG output coupler and by an RFL using no FBG output coupler (only 4% Fresnel reflection) is shown in Fig. 3. These two configurations produced the greatest and the least amount of Stokes powers respectively. The 90% FBG configuration has an optical conversion efficiency of 56%, a Stokes threshold of ~4 W and a slope efficiency of 87%. The 4% configuration has an optical conversion efficiency of 41%, a Stokes threshold of ~7 W and a slope efficiency of 126% (at the powers measured). At higher pump powers, the slope efficiencies are expected to moderate and roll over due to pump depletion. Other configurations (not shown) performed comparably.
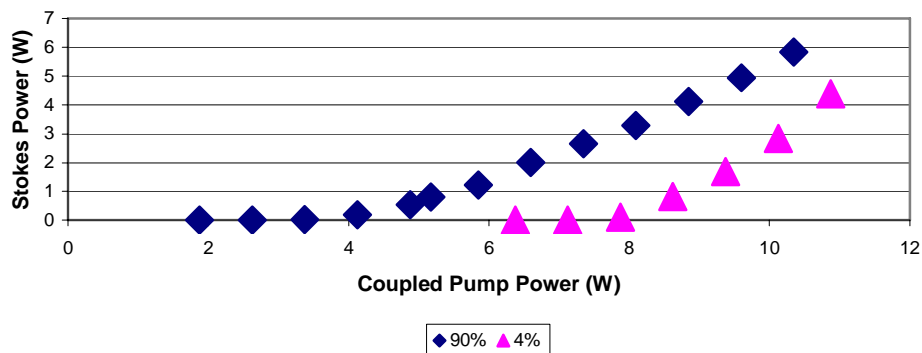

Fig. 3. Stokes power as a function of coupled pump power for the RFL beam combiner with an FBG which is 90% reflective at the Stokes wavelength and a configuration with no FBG (i.e. uses the 4% Fresnel reflection as the output coupler).

Beam quality measurements of the Stokes beams generated by various FBG output coupler configurations using a 2500 m length of fiber are shown in Fig. 4. Beam quality in the form of M^2 was calculated by characterizing the diameter of the beam at about 20

different locations as it traversed the focus of an f=300 mm lens. The beam diameter at each location was determined using the average of 50 images taken with an Alpha NIR InGaAs camera. Neutral density filters were used to prevent saturation of the camera. A least-squared fit was used to determine the value of M^2.
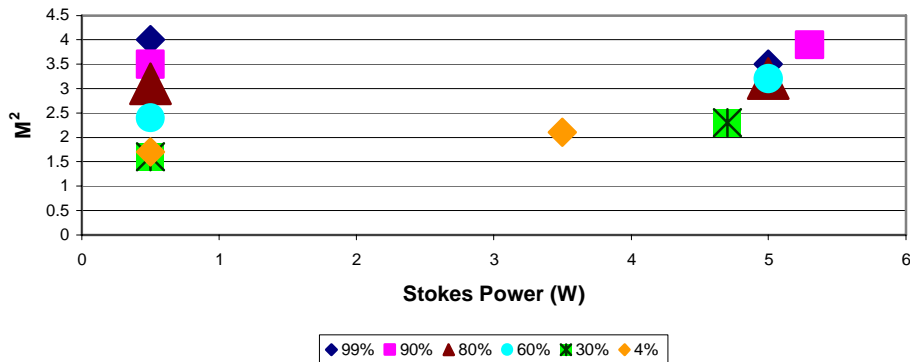

Fig. 4. Beam quality of the output of a 2500 m long RFL with various output coupler FBGs for two different Stokes output powers. Each configuration is identified by the reflectivity of the output coupler FBG as given by the manufacturer. The label "4%" indicates that no FBG is used—instead the output coupler is the Fresnel reflection of the flat cleaved face of the fiber.

As can be seen in Fig. 4, there is a definite correlation between the beam quality of the Stokes beam and the output coupler FBG. The gratings with a lower reflectivity produce Stokes output with greater beam quality than do gratings with a higher reflectivity, indicating that higher reflectivity FGBs cause more Stokes power to oscillate in higher order modes. There is also some correlation between the Stokes power and the beam quality. M^2 appears to increase with Stokes power. One exception was noted for the 99% grating, where the M^2 decreases slightly after 0.5 W of Stokes power. While the 90% grating produced the greatest Stokes power, the configuration with a 4% output coupler produced the best beam quality.

The Stokes output can also be characterized in terms of brightness, which is defined as

$$B = \frac{P}{(M^2)^2 \lambda},\qquad(1)$$

where P is the power, M^2 is a measure of the beam quality and λ is the wavelength. The 4.4 W of Stokes power (M^2=2.1) produced by the 4% output coupler configuration was three times brighter than that of the 10.8 W combined pump beam (M^2=5.8). On the other hand, the 5.8 W Stokes power (M^2=3.5) produced using the 90% output coupler was 1.4 times brighter than the pump beam.

The spectral output of the RFL with the 4% output coupler at 2 W of power, shown in Figs. 5(a), contains only a single narrowband linewidth (0.8 nm) from a single Stokes order. The spectral content produced by the 90% reflectivity grating at 2 W of power, shown in Fig. 5(b), contains two Stokes orders. The 2nd Stokes order is generated in this configuration due to the increased intracavity intensity associated with using a high reflectivity FBG as an output coupler. At 2 W of Stokes power, the 1st Stokes order produced with the 90% output coupler is composed of a single peak with a linewidth centered near 1117nm of 0.8nm, as shown in Fig. 6(a). At 5.8 W of Stokes power power, the 1st Stokes order exhibits multiple peaks with the highest peak centered on 1115.5nm as shown in Fig. 6(b). These peaks are attributable to the variable reflectivity and unique wavelength associated with the various modes reflected by an FBG that is written to a multimode fiber. As Stokes power increases, the output wavelength can shift lower, which corresponds to shifting to higher order spatial modes allowed by the multimode FBG. These higher order spatial modes reduce the beam quality of the output Stokes beam, somewhat offsetting the beam cleanup effect.
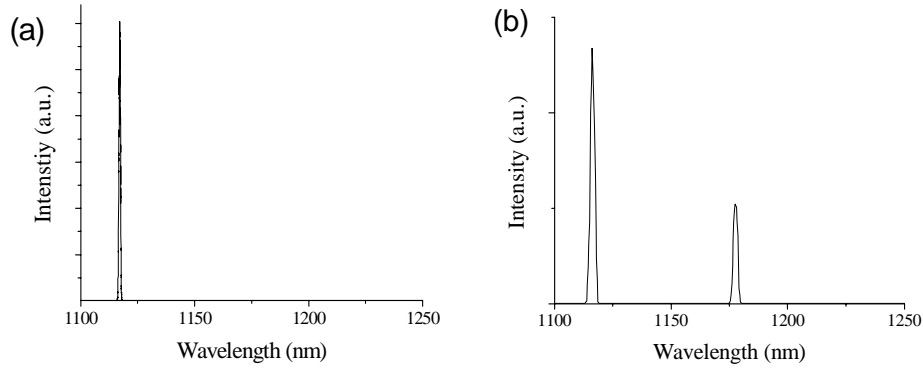
Fig. 5. Spectrum produced by the 4% output coupler at 2 W of power (a) and by the 90% output coupler at 2 W of Stokes power (b).
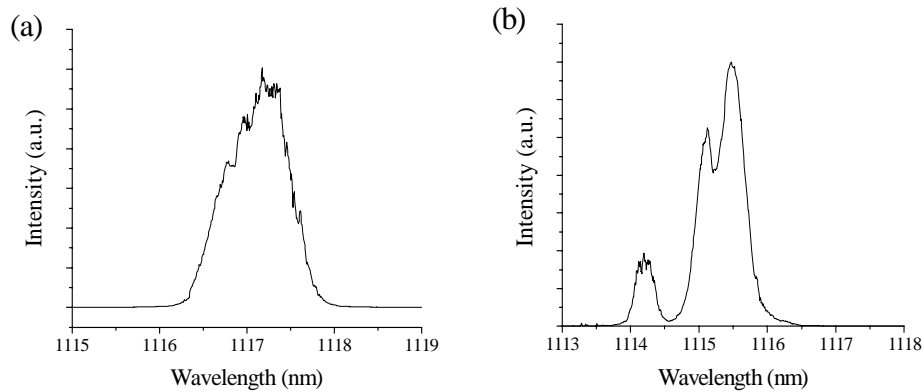

Fig. 6. Spectrum produced by the 90% reflectivity FBG output coupler; (a) shows the spectrum at 2 W of power, (b) shows the multiple peaks characteristic of high power operation at 5.8 W of Stokes power. Note that multiple peaks correspond to resonant modes resulting from the multimode properties of the FBG.

4. Conclusion

In conclusion, we have demonstrated that an RFL based on multimode graded-index fiber can be used as a method for SRS beam combination. This technique produces a 4.4 W Stokes beam which is up to 300% brighter than the pump beams, or a 5.8 W beam that is 140% brighter than the pump beams. The optical conversion efficiency of the 5.8W beam is shown to be up to 56%, which is to our knowledge the highest optical conversion efficiency of any multimode pumped RFL. This technique also produces slope efficiencies which approach or even exceed unity at the powers tested. Similar to Baek and Roh [10], we also observed near single-mode Stokes output under conditions of low Stokes power and low-reflectivity gratings. As Stokes power and grating reflectivity increase, we have shown that the beam cleanup effect decreases. While this work demonstrated the feasibility of combining 1064 nm pumps to generate a single Stokes beam, the technique can be fully generalized to other wavelengths of interest which can be transmitted through an optical fiber.

Acknowledgments