Power Scaling of Single-Frequency Hybrid Brillouin/Ytterbium Fiber Lasers

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Abstract—A coupled-wave rate-equation model, including multiple-order stimulated Brillouin scattering (SBS), is used to study power scaling of hybrid Brillouin/Ytterbium fiber lasers. To validate the model, a single-frequency, Brillouin/Ytterbium fiber laser was built with a laser output of 40 mW and an optical signal-to-noise ratio greater than 50 dB. The numerical model simulation agrees with the measurements in both fully and partially injection locked regimes. To scale up the laser’s output power, a dual-clad architecture is proposed. In this new configuration, the active Yb-doped fiber provides the nonlinear Brillouin gain as well as the gain resulting from the excited Yb ions. Numerical modeling including three Stokes orders shows that over 5 W of single-frequency laser output can be achieved with a side-mode suppression ratio (SMSR) of greater than 80 dB. Beyond this power, multi-order SBS affects the laser efficiency and SMSR.

Index Terms—Brillouin scattering, fiber laser, high-power laser, single-frequency laser.

I. INTRODUCTION

SINGLE-FREQUENCY fiber lasers have potential applications in sensing [1], ranging [2], data storage [3], communications [4], and interferometry [5]. Watt-level single-frequency output has been achieved from distributed-feedback fiber lasers [6], short linear-cavity fiber lasers [7], and ring-cavity fiber lasers with narrow-bandwidth filters [8]. Pump coupling and thermal effects limit the output powers of these lasers. Another approach for generating high-power single-frequency sources is by using master-oscillator/power-amplifier (MOPA) schemes with a single-frequency seed [9], [10]. However, the amplified spontaneous emission noise degrades the optical signal-to-noise ratio (OSNR) of these single-frequency sources. Furthermore, single-frequency performance is limited by multiple-order stimulated Brillouin scattering (SBS) in fiber amplifiers because of the narrow bandwidth of the seed [10]. From the system complexity point of view, a MOPA architecture is more complicated than a single-frequency oscillator.

SBS has a narrow gain bandwidth and can therefore be used as a narrowband filter for generating single-frequency laser output by inserting a long section of passive fiber into the ring cavity of a rare-earth fiber laser. Although such a laser will nominally oscillate in many longitudinal modes, the injection of narrowband light will generate a Stokes wave in the long passive fiber, and the laser will injection lock to this Stokes wave producing single-frequency output. In this way, hybrid Brillouin/rare-earth fiber lasers have been demonstrated by using the conventional gain in a rare-earth doped fiber and the nonlinear Brillouin gain in a section of passive fiber [11]–[13]. Single-frequency output as high as tens of milliwatts has been achieved and is limited by the single-spatial-mode pump power. Higher single-frequency output powers from hybrid Brillouin/rare-earth fiber lasers have not yet been studied. In this paper, a numerical model with multiple-order SBS is used to study the power scalability of hybrid ring fiber lasers to high powers. In Section II, the general model describes the light and population in the Yb-doped fiber (YDF), including multiple-SBS. In Section III, a hybrid laser is built and compared to simulation results to validate the model. In Section IV, the model is applied to a dual-clad ring cavity to investigate the power scalability. A discussion and concluding remarks are presented in Section V.

II. NUMERICAL MODEL

The general architecture of a single-frequency hybrid Brillouin/Ytterbium fiber laser is shown in Fig. 1. The active fiber can be a core-pumped or dual-clad YDF, depending on the spatial mode properties of the pump laser’s diodes. The ring cavity length must be less than 16 m to generate single-frequency output using the ~20 MHz Brillouin gain bandwidth in the fiber medium. The pump coupler can be a wavelength-division multiplexer (WDM) or a dual-clad pump combiner. The pump laser’s wavelength can be 915 nm or 976 nm. The Brillouin pump must be a narrowband, single-longitudinal-mode laser source.

The numerical model describes the interaction between the pump wave, the Brillouin pump wave, and multiple orders of Stokes waves. Specifically, in the active fiber section, the general coupled-wave equation can be written as [10]
inverse of the effective mode area; and

\[ \text{Fig. 1. Schematic diagram of a generic single-frequency hybrid Brillouin/ytterbium fiber laser.} \]

\[
\frac{dP_i}{dz} = \pm \left( \sigma_i^+ + \sigma_i^- \right) n_2 - \sigma_i^0 \right) N_i \left( P_i^n - P_i^0 \right) \\
\pm \varepsilon g \sigma_i^0 \left( P_i^n - P_i^0 \right) \\
\pm \gamma n_2 \left( P_i^n - P_i^0 \right)
\]

where \( P_i^n \) is the power of the \( i \)th optical wave including the pump wave and Brillouin seed; and \( \sigma_i^+ \) and \( \sigma_i^- \) denote the propagation direction; \( \sigma_i^0 \) are the emission and absorption cross-sections of the ytterbium ions at the \( i \)th optical wavelength; \( N_i \) is the doping density; \( \Gamma_i \) is the overlap factor between the \( i \)th optical wave and the doping ions; \( a_i \) is the attenuation factor at the \( i \)th wavelength; \( W \) is the inverse of the effective mode area; and \( g_b \) is the net Brillouin gain coefficient; \( \varepsilon g_n \) is the gain coefficient for the spontaneous process, where \( P_0 = h \nu / \Delta \nu \) and \( \Delta \nu \) is the linewidth of the Brillouin pump beam in Hz; and \( n_2 \) is the population inversion in the active fiber section and can be written as [10]

\[
n_2(c) = \frac{\sum_i \sigma_i^+ \Gamma_i \left( P_i^n + P_i^- \right) \left( Ahc / \lambda_i \right)^{-1}}{\pi + \sum_i \sigma_i^+ + \sigma_i^- \Gamma_i \left( P_i^n + P_i^- \right) \left( Ahc / \lambda_i \right)^{-1}}
\]

where \( A \) is the effective mode area, \( \tau_i \) is the upper state lifetime, and \( \lambda_i \) is the wavelength of the \( i \)th optical wave in the YDF. In applying this model, the effect of SBS on the pump wave is neglected because of its large spectral bandwidth. The \( P_{-1} \) term is not valid for the Brillouin seed. The performance of single-frequency hybrid Brillouin/ytterbium fiber lasers can be modeled by solving (1) and (2) with appropriate boundary conditions for each wave in the cavity. The finite-difference method, the shooting method, and the relaxation method are used to find the steady-state solution by iterating many round-trips in the ring cavity [14], [15]. In the model described above, the positive \( z \) axis is counterclockwise, following the direction of the Brillouin pump, and the origin is located at the output coupler/isolator, with the short section of fiber in between assumed to be negligible.

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**III. EXPERIMENTAL VERIFICATION**

A single-frequency hybrid Brillouin/ytterbium fiber laser was built to validate the numerical model presented in Section II. The experimental setup of the hybrid fiber laser is shown in Fig. 2. A WDM was used to couple the 976 nm pump power into the core of the YDF. The active fiber was 40 cm long and highly ytterbium doped with a pump absorption rate of 12 dB/cm. A 50 kHz-bandwidth laser source (Koheras) at 1053 nm was seeded through a 80/20 coupler into the laser cavity. When the Brillouin pump was injected into the cavity, it was first amplified by the YDF. The passive single-mode (SM) fiber was about 10 m long and functioned as the Brillouin gain medium. The SBS stokes wave was generated in the SM fiber and circulated in the ring cavity. An isolator with an insertion loss of 1.5 dB at 1053 nm was used to prevent the laser from injection locking at the Brillouin pump wavelength. The 80/20 coupler coupled the Brillouin pump into the cavity and the laser light out of the cavity through the 80% port, while only 20% of the laser light remained in the cavity. Although many coupling configurations were tested, this configuration was experimentally found to yield the highest output power by balancing the required Brillouin pump power against the cavity loss, which was compensated by the Yb amplifier.

The laser power was measured using another coupler and back calculated to obtain the laser output power as shown in Fig. 2. Fig. 3 displays the output power as a function of

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**Fig. 3. Laser output power as a function of a 980 nm pump for three different Brillouin pump powers.**
the pump power for three different Brillouin pump powers. When the Brillouin pump was 9 mW, the laser threshold was 125 mW and the laser output power reached 40 mW at a pump power of 370 mW. The high threshold was caused by the low-coupling ratio of the coupler (20%). The 40-cm length of the highly doped ytterbium fiber was long compared to the pump absorption but necessary to shift the gain peak, making the free-running laser work at 1051 nm, which is sufficiently close enough to the Stokes wavelength of 1053.05 nm for easy injection locking. Fig. 3 shows that as the Brillouin pump power was increased from 9 mW to 18 mW, the laser threshold increased and thus the output power decreased. This was due to the gain saturation in the YDF by the Brillouin pump, which led to less-available gain for amplification of the Stokes wave and thus lower output power.

The OSNR was measured with an optical spectrum analyzer (OSA) at 40 mW output power. The laser output spectrum, shown in Fig. 4, indicated an OSNR greater than 50 dB. Additionally, the Brillouin pump wavelength was 1053.05 nm, while the fiber laser wavelength was 1053.1 nm. The frequency difference between the Brillouin pump and the laser output matched the expected Stokes shift of the SBS at the working wavelength.

Single-frequency output was verified with a scanning Fabry-Perot (FP) spectrometer. The FP cavity length was 15 cm, corresponding to a free spectral range of 1 GHz. The FP cavity had a finesse of 160, giving a resolution of 6.25 MHz. Since the laser cavity length was 12 m, corresponding to 16 MHz mode spacing, the resonant modes of the ring cavity could be resolved by the FP spectrometer. The measurement result shown in Fig. 5 clearly shows single-frequency operation. Although multiple cavity modes can in principle operate within an ∼20 MHz SBS gain profile, the SBS line shape provides significant longitudinal mode discrimination such that only a single-mode will operate in the ring cavity. No mode hopping was observed in the measurement at any pump level.

The hybrid laser shows high stability, as opposed to many short linear-cavity, single-frequency fiber lasers, which have short cavity photon lifetimes and can easily suffer from self-pulsations [16]. From the oscilloscope, the continuous wave laser output was stable for over 2 h without any self-pulsations.

This high stability can be explained by the saturation of the YDF caused by Brillouin pump pre-amplification in the fiber laser [17]. When the Brillouin pump is sufficiently large, there is no free gain in the saturated Yb fiber, and thus no extra population inversion is built up.

When there is no Brillouin pump injected into the laser cavity, the free-running laser works with multiple longitudinal modes at 1051 nm. In this sense, the Brillouin/ytterbium fiber laser can be treated as a Yb-fiber–laser injection locked by the Stokes wave generated in the ring cavity [18], where the isolator prevents the laser from injection locking to the Brillouin pump. For a conventional ring-cavity Brillouin laser, the pump-coupling ratio depends on the cavity loss and the round-trip phase shift in the cavity, which must be an integer multiple of 2π to achieve the intensity enhancement (maximum intensity). For this reason, piezo controllers or tunable couplers are normally required to maintain resonance between the cavity and the Brillouin pump wavelength [19]–[22]. This added complication yields a Brillouin pump-intensity enhancement determined by the finesse of the resonator [20], which can be typically of the order of 10–1000. In the hybrid-laser configuration, an isolator in the cavity prevents the pump wave from traveling multiple round-trips and, thus, eliminates the need for cavity or frequency control. This results in a loss of Brillouin pump intensity, which is compensated for by inserting a pumped active fiber into the cavity, i.e., a hybrid laser. In the demonstrated configuration shown in Fig. 2, the short-length-fiber cavity makes the laser less influenced by mechanical and thermal fluctuations and, therefore, entirely free from mode hopping [23]. Furthermore, the demonstrated hybrid fiber laser generates higher output power than the injected Brillouin pump, as shown in Fig. 3, making the laser advantageous to previously demonstrated hybrid lasers [11].

A. Full Injection Locking and Gain Saturation

Applying (1) and (2) to the active fiber section, the interaction between the 976 nm pump, the Brillouin pump, and
multiple-order Stokes waves can be written as

\[
\begin{align*}
\frac{dP_0}{dz} &= -\left(\sigma_i + \sigma_s^0\right) n_2 - \sigma_i^0 \left[ N_0 P_0 F_p^2 + \alpha_P P_0^2 - \alpha P_0 P_0^2 + \beta S B P_0^2 \right] \\
\frac{dP_1}{dz} &= \left(\sigma_i + \sigma_s^0\right) n_2 - \sigma_i^0 \left[ N_0 P_0 L_1 + \alpha P_0 P_1^2 - \alpha P_0 P_0^2 + \beta S B P_0 P_1 \right] \\
\frac{dP_0}{dz} &= \left(\sigma_i + \sigma_s^0\right) n_2 - \sigma_i^0 \left[ N_0 P_0 P_0^2 + \alpha P_0 P_0^2 - \alpha P_0 P_0^2 + \beta S B P_0 P_0 \right] \\
\frac{dP_1}{dz} &= \left(\sigma_i + \sigma_s^0\right) n_2 - \sigma_i^0 \left[ N_0 P_0 L_2 + \alpha P_0 P_1^2 - \alpha P_0 P_0^2 + \beta S B P_0 P_1 \right] + \beta S B P_0 P_1 + \beta S B P_0 P_1
\end{align*}
\]

where \(P_0\) is the 976 nm pump wave, \(P_1\) is the first-order Stokes wave, and \(P_0^2\) is the second-order Stokes wave. The population inversion \(n_2\) is identical to the term in (2), where the inversion is induced by the four waves described by (3). \(\sigma_i^0\) and \(\sigma_s^0\) are the emission and absorption cross-sections of the 9th wave, whose values are taken from [24]. The upper-state lifetime is measured as 0.17 ms for the highly doped fiber [25]. The polarized Brillouin gain coefficient is 4.6 \times 10^{-11} m/W. In SM fibers, the Brillouin gain is reduced by a factor of 0.667, yielding \(g_B = 3 \times 10^{-11} m/W\) [26], [27].

In the passive-fiber section, the same set of equations are applied with \(n_2\) and the stimulated absorption and emission cross-sections set to zero. The boundary conditions for the ring cavity fiber laser are

\[
\begin{align*}
P_F(L_1) &= P_p \\
P_0(0) &= \rho P_0 \\
P_1(0) &= \rho_0 P_0 (L_1 + L_2) \\
P_0(0) &= 0
\end{align*}
\]

where \(P_p\) is the 976 nm pump power and \(P_0\) is the Brillouin pump power. \(L_1\) and \(L_2\) are the lengths of the Yb-doped and passive fibers, respectively. The coupling ratio of the coupler \(\rho\) is 20%. The insertion loss of the isolator \(\rho_0\) is 0.6. Relating to Fig. 2, the point \(z = 0\) indicates where the Brillouin pump is coupled into the cavity. The positive \(z\)-axis is toward the end of the SM fiber. The zero boundary condition for \(P_0^2\) is due to the isolator. The isolator typically has an isolation of 20-30 dB, such that the power at \(z = 0\) is small but nonzero. Including this would make the calculation significantly more complex without significantly improving the accuracy of the result. Equations (2)-(4) are solved with the finite-difference method [14] and the relaxation and shooting methods [15]. The loss coefficient of the fiber is 3 \times 10^{-4}. The additional parameters used in the simulation are shown in Tables I and II.

When the 976 nm pump power is 370 mW and the Brillouin pump power is 9 mW, the power distributions of the optical waves inside the laser cavity are as shown in Fig. 6. The 976 nm pump \(P_p\) was quickly absorbed into the active fiber because of the high ytterbium-doping density in the active fiber. Experimentally, the active fiber length of 40 cm was chosen so that the free-running laser peaks (1051 nm) were sufficiently close to the Brillouin Stokes wavelength (1053.05 nm) to easily injection lock the laser. The Brillouin pump was amplified by the YDF before entering the passive fiber. The 9 mW Brillouin pump was effectively tuned into the 80 mW seed for SBS generation in the passive fiber. This feature makes this particular hybrid configuration power scalable without scaling the narrow-line Brillouin pump power.

Fig. 6 shows that the first-order Stokes wave was generated from the scattering of the Brillouin pump in the passive fiber and amplified by the active fiber. Note that the Brillouin seed was not fully converted into the first Stokes wave. A longer fiber length could be used for full conversion, but would lead to multiple-longitudinal-mode operation. Due to the intracavity isolator, the second-order Stokes wave is 100 dB lower than the first-order Stokes wave. The absence of second-order Stokes motivates the power scaling of this hybrid configuration.

When the laser was fully injection locked to the Brillouin Stokes wave, the measured output power (see Fig. 3) decreased as the Brillouin pump power increased. This can be explained by the gain saturation induced by the Brillouin pump and Stokes wave amplification in the YDF. Fig. 7 shows simulated laser output power versus the seeded Brillouin pump as the 976 nm pump was kept at 370 mW. The simulation result agrees with the measured output power reduction, also shown in the figure, which was caused by the gain saturation generated by the Brillouin pump in the active fiber. When the Brillouin pump power is increased for the fiber laser, the gain in the active fiber is more deeply saturated and, therefore, the first-order Stokes wave power decreases.

B. Partial Injection Locking

When the Brillouin pump power is relatively low, the hybrid Brillouin/ytterbium fiber laser will not be fully injection locked to the Stokes wave. The measured OSNR versus the Brillouin pump power is shown in Fig. 8 with a 976 nm pump power of 370 mW. When the Brillouin pump is less than 8 mW, the
Fig. 6. Power distributions of the optical waves in the active and passive fibers. $P_p = 370$ mW, $P_b = 9$ mW.

Fig. 7. Simulated and measured output power as a function of Brillouin pump power when the pump power $P_p$ is 370 mW.

When the Brillouin pump is between 4 mW and 9 mW, the laser is partially injection locked to the Brillouin Stokes wavelength. When the Brillouin pump is greater than 9 mW, the laser is fully injection locked at the Stokes wavelength of the pump. To model the partial injection locking of the hybrid Brillouin/ytterbium fiber laser, a revised numerical model based on (1) and (2) is applied to the fiber laser. In the active fiber section, the interaction between the 976 nm pump wave, the first-order Brillouin Stokes wave, and the free-running laser wave can be written as

$$\frac{dP_1}{dz} = -\left(\left(\sigma_e + \sigma_a\right) n_2 - \sigma_a\right) N_0 \frac{\Gamma_1 P_1 + \alpha P_1}{\Gamma_1 P_1}$$

$$\frac{dP_0}{dz} = \frac{\left(\sigma_e + \sigma_a\right) n_2 - \sigma_a}{\Gamma_1 P_0 + \alpha P_0}$$

$$\frac{dP_F}{dz} = -\left(\left(\sigma_e + \sigma_a\right) n_2 - \sigma_a\right) N_0 \frac{\Gamma_1 P_F + \alpha P_F}{\Gamma_1 P_F}$$

where $P_F$ is the free-running laser signal wave. There is no SBS term for the free-running mode because the bandwidth of the signal is much larger than the SBS gain bandwidth in the fiber. Due to the isolator in the ring cavity, the second-order SBS is negligible, as verified in Section III-A. The free-running laser wavelength is 1051 nm. In the passive-fiber section, the set of equations is applied with $n_2$ and the stimulated absorption and emission cross-sections set to zero.

The boundary conditions for (5) are

$$P_1 (L_1) = P_p$$

$$P_0 (0) = \rho P_b$$

$$P_F (0) = \rho P_F (L_1 + L_2)$$

$$P_F (0) = \rho P_F (L_1 + L_2)$$

These boundary conditions explicitly show the competition between the Stokes wave $P_1$ and the free-running wave $P_F$.

When the 976 nm pump is kept at a constant level, the injection-locking quality of the laser, defined by the OSNR, varies as the Brillouin pump is changed. The simulated OSNR is plotted with the measured OSNR in Fig. 8. In the figure, when the free-running laser power is greater than or equal to the Brillouin Stokes power, the OSNR is defined as 0 dB. As
IV. POWER SCALING OF SINGLE-FREQUENCY HYBRID BRILLOUIN/YTTERBIUM FIBER LASER

The numerical model presented in the previous section describes single-frequency hybrid fiber lasers with high accuracy and can therefore be used to explore power scaling. Higher output power can be expected from such lasers when the pump power is further increased. The model of (1) can be used to predict the performance of high-power single-frequency Brillouin/Ytterbium fiber lasers, but the laser configuration must change. In high-power fiber lasers, the pump power is coupled into the dual-clad active fiber by using pump combiners and multimode pump laser diodes. This means that the active fiber must be moved from the system. As such, the fiber length should be less than 16 m. Therefore, the passive fiber length is 15 m and the active fiber is zero.

one can see in Fig. 8, excellent agreement is achieved between the simulation and measurement results. When the Brillouin pump power is below the threshold value of 9 mW, the fiber laser is not fully injection locked. Beyond this threshold value, the laser operates in a single-frequency, fully injection locked to the Brillouin Stokes wave.

For the numerical study, the active fiber length for the laser shown in Fig. 1 is 15 m and the passive fiber length is zero. The coupler has a coupling ratio of 70/30, where 70% of the laser light is kept in the ring cavity. The coupled wave (1) in the active fiber can be written as

\[
\begin{align*}
\frac{dP_1}{dz} &= -\left[\sigma_{11} + \sigma_{12}\right] n_2 - \sigma_{22} n_2 G_p P_1 + \alpha P_1^3 \\
\frac{dP_2}{dz} &= + \left[\sigma_{21} + \sigma_{22}\right] n_2 - \sigma_{12} n_2 G_p P_2 - \alpha P_2^3 \\
\frac{dP_3}{dz} &= -\left[\sigma_{11} + \sigma_{12}\right] n_2 + \sigma_{12} n_2 G_p P_3 + \alpha P_3^3 \\
\frac{dP_4}{dz} &= -\left[\sigma_{21} + \sigma_{22}\right] n_2 + \sigma_{21} n_2 G_p P_4 - \alpha P_4^3 \\
\frac{dP_5}{dz} &= + \left[\sigma_{11} + \sigma_{12}\right] n_2 - \sigma_{22} n_2 G_p P_5 - \alpha P_5^3
\end{align*}
\]

where \(P_1^0\) is the Brillouin pump power. The insertion loss of the isolator \(\beta\) is 0.6. The coupling ratio of the coupler \(\rho\) is 70%.
Equations (2), (7), and (8) are solved with finite difference and shooting methods. With the Brillouin pump power set at 400 mW, the first and second-order Stokes powers are shown in Fig. 9. The first-order Stokes output power reached 1 W before the second-order Stokes power started to degrade the laser efficiency. Due to the isolator, the second-order SBS did not resonate as a laser mode, making possible the high-power single-frequency output.

Fig. 10 shows the power distribution of the first and second-order Stokes waves with the 915 nm pump and Brillouin pump in the active fiber in the linear and log scales. The output power was 1.2 W and the Brillouin pump power was 400 mW. From the figure, one can see that 80% of the 915 nm pump power was absorbed by the active fiber. The Brillouin pump propagated from the left-hand side and was amplified in the active fiber and coupled into the first-order Stokes waves. The first-order Stokes wave propagated from right-hand side, first attenuating before being amplified. This attenuation was caused by cascaded SBS, where part of the first-order Stokes wave was transferred to the second-order Stokes wave, which grew rapidly toward the right end of the active fiber. The intracavity power of the first-order Stokes wave was nearly 4 W at the left-hand side, where 30% of the light was coupled out as laser output.

The minimum Brillouin pump power required for full injection locking were calculated with (5) and shown in Fig. 11. The required Brillouin pump power for a 2 W single-frequency output power is 400 mW. Below this Brillouin pump threshold, the laser was only partially injection locked with relatively low OSNR.

Due to the coupler direction in the laser setup, the single-frequency performance of the laser was ultimately limited by the third-order Stokes wave, which propagated in the same direction as the first-order Stokes and was not blocked by the isolator. The laser output side-mode suppression ratio (SMSR) was determined by the power ratio between the first-order Stokes wave and the third-order Stokes wave. Fig. 12 shows the simulated SMSR as the laser output power varies between zero and 2 W. When the output power increased beyond 1.8 W, the third-order Stokes power became pronounced and degraded the SMSR below 50 dB.

The output coupler plays an important role in the single-frequency hybrid Brillouin/ytterbium fiber laser. The coupler ratio dictates the tradeoff between the intracavity power and the output power and also affects the amount of Brillouin pump that is injected into the laser cavity. Fig. 13 shows the second-order Stokes threshold pump powers as a function of the coupler ratio. The threshold pump power decreased as the coupler ratio was increased because of the increased intracavity first-order Stokes wave power. Fig. 14 shows the first-order Stokes output power and the required Brillouin pump power as a function of coupling ratio when the pump powers were set...
at the second-order Stokes threshold pump powers. The first-order Stokes output power therefore represents the highest-achievable output power before second-order SBS degrades the laser efficiency. Although higher output power can be achieved by the laser using a lower coupler ratio, a higher Brillouin pump seed is required to fully injection lock the Stokes output. The SMSR of the laser as a function of the coupling ratio is shown in Fig. 15. The output SMSR remained above 80 dB regardless of coupler ratios since the laser was operating at the second-order SBS threshold. This implies that the specific cavity design has little impact on the spectral quality of the laser, provided that second-order SBS is avoided. Figs. 13-15 demonstrate that up to 5 W of single-frequency output power can be achieved in the hybrid Brillouin/ytterbium fiber laser at high efficiency with a side-mode-suppression ratio greater than 80 dB. In fact, 1 W of single-frequency output has been recently demonstrated in such a hybrid laser using dual-clad fiber [28].

V. DISCUSSION AND CONCLUSION

In hybrid Brillouin/ytterbium fiber lasers, SBS generates the first-order Stokes output but also limits the output power because of the onset of higher-order Stokes waves. Therefore, by using several of the known SBS-reduction techniques, this laser configuration can be scaled to even higher power levels. For example, by reducing the active fiber length by using higher Yb-doping density or brighter pumps, the nonlinear interaction length is correspondingly reduced and the second-order Stokes threshold can be increased. Increasing the fiber mode area reduces the intensity at a given power level and therefore increases the SBS thresholds. By scaling the SM fiber results of Section IV to a 20 µm large-mode-area fiber, the output power shown in the figures can be scaled up by a factor of 10.

In conclusion, a coupled-wave rate-equation model, including multiple-order SBS was used to study power scaling of hybrid Brillouin/ytterbium fiber lasers. To validate the model, a single-frequency, Brillouin/ytterbium fiber laser was built with a laser output of 40 mW and an OSNR of greater than 50 dB. The numerical model simulation agreed with the measurements in both fully and partially injection locked regimes. To scale up the laser output power, a dual-clad, single-frequency hybrid Brillouin/ytterbium fiber laser was proposed. In this new configuration, the active YDF provided the nonlinear SBS gain as well as the gain resulting from the excited Yb ions. Numerical modeling including three Stokes orders showed that over 5 W of single-frequency laser output could be achieved with an SMSR of greater than 80 dB. Beyond this power, multi-order SBS affected the laser efficiency and SMSR.

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