High-energy pulsed Raman fiber laser for biological tissue coagulation

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Abstract: We demonstrate a high-energy pulsed Raman fiber laser (RFL) with an emission wavelength of 1.44 μm, corresponding to an absorption peak of water. Microsecond pulses with >20 mJ/pulse and >40 W peak power were generated, well above the threshold for tissue coagulation and ablation. Here, we focus on the optical characterization and optimization of high-energy and high-power RFLs excited by an ytterbium fiber laser, comparing three configurations that use different Raman gain fibers, but all of which were prepared with a one-side opened, free-run mode without output mirrors. We show that the free-run configuration can generate sufficiently high energy without requiring a closed cavity design. Experimental RFL characteristics corresponded well with numerical simulations. We discuss the Stokes beam generation process in our system and loss mechanisms mainly associated with fiber Bragg gratings.

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1. Introduction

High-power fiber lasers have gained growing attention for medical therapeutic applications [1–3]. Particularly, fiber laser operation near 1.44-μm or 1.9-μm wavelength has been a major subject of interest for tissue coagulation and ablation, owing to prominent water absorption at these wavelengths and therefore relatively uniform absorption across different tissues as well as the ability to exploit absorption gradients to tailor the depth of energy deposition [4]. While 1.44-μm medical lasers have typically provided low power (<2 W) [5], more than 100 W has been achieved at 1.9-μm using thulium fiber lasers. However, few fiber optic components such as circulators, couplers, modulators and multiplexers are readily available in the thulium emission band, a point in favor of 1.44-μm sources. Additionally, coupling therapeutic laser emission through catheter-based imaging systems operating near 1.3 μm further motivates the development of high-power sources at 1.44 μm. Such multiplexed systems, e.g. based on optical coherence tomography (OCT) or optical frequency domain imaging (OFDI) [6], would be attractive for clinical applications such as laser-induced tissue marking for precise image-guided biopsy and longitudinal surveillance of suspicious lesions in the gastrointestinal tract [7].

Previously, a continuous-wave (CW) fiber laser with an output power of ~380 mW at 1480-nm wavelength was demonstrated for tissue marking and biopsy guidance [7]. However, performance of this system was inhibited by the low laser energy available at the tissue surface, inefficient heat deposition due to thermal diffusion under CW optical irradiation, and spectral mismatch between the laser wavelength and the absorption peak of water. These shortcomings slowed down the laser-marking process, requiring stationary irradiation over a few to several seconds to generate a mark that was endoscopically apparent. Therefore, laser marking could not be done simultaneously with imaging, and the marking location could not be monitored in real time. The use of pulsed lasers can be an effective approach to deliver thermal energy with temporal confinement and therefore facilitate efficient tissue coagulation [8]. For example, although the CW laser marking parameters of Suter et al. [7] suggest that more than a Joule of energy was required to induce coagulation and a visible mark, numerical models [4,9] can be used to show that when laser energy is delivered on a time scale that is short relative to thermal diffusion, the threshold for marking may be reduced more than one hundred-fold. Motivated by such models, we sought to develop a 1440-nm laser capable of delivering pulses with ~10 mJ of energy and with temporal duration in the 100–500 μs. Operating on this time scale, tissue marking could be
achieved simultaneously with imaging, thereby improving accuracy and allowing confirmation of mark location and viability.

Stimulated Raman scattering (SRS) has been utilized to develop high-power fiber lasers having wavelengths that are difficult to access directly with conventional gain media. In the SRS process, the amount of the Stokes frequency shift is intrinsically determined by the irradiated medium in which a quantum conversion increases proportionally with the complex part of the third-order nonlinear permittivity \[10,11\]. As this allows a design flexibility for laser output spectra, a great deal of effort has focused on developing RFLs with a spectral range of 1400–1500 nm, mostly as pump lasers for optical communications. Various RFLs have been fabricated using germanosilicate or phosphosilicate glass fiber as Raman gain media. CW-mode power levels of 1.9 W at 1450 nm \[5\], 81 W at 1480 nm \[12\], and recently 301 W at 1480 nm \[13\] have been achieved.

In this work, we demonstrate single-transverse-mode, pulsed RFLs that generate microsecond pulses with >20 mJ energy (>40 W peak) at a designed output wavelength of 1436 nm. The pulse energy exceeds the requirement for tissue coagulation (a few mJ within a 60-μm focal spot), which can greatly enhance tissue marking efficiency. We show that our RFL configurations using a one-side-opened, free-run mode without rear mirrors can allow sufficient Raman conversion to the Stokes order of ~1440-nm wavelength from the pump beam at 1090 nm. For systematic investigation, three RFL configurations were comparatively characterized in terms of output powers, optical spectra, and longitudinal power profiles within Raman fiber media. Experimental results were found to be in agreement with numerical simulations that were obtained by solving coupled ordinary differential equations with a discrete step evolution along the longitudinal axis of the Raman gain fiber.

2. RFL configurations

The RFLs were designed to operate at 1436-nm wavelength using cascaded SRS initially pumped by a 1090-nm ytterbium fiber laser (nLight, Vancouver, WA; Model No. NL-QCWF-400-1090) having a spectral width of <5 nm and capable of emitting up to 400-W cw. The output beam was achieved by 5-step Stokes conversion in fused silica fibers from 1090 nm to 1436 nm in a cascaded manner. We compared three configurations as shown in Fig. 1. All RFL systems were operated in a free-run configuration with mirrors placed only on the pump side of the Raman gain medium; a normal cleaved fiber end with nominal 4% Fresnel reflection formed the output coupler. Each RFL consisted of the pump fiber laser, a mode-field adapter, fiber Bragg grating (FBG) mirrors, and a different type of Raman gain fiber. Pulsed operation was achieved by gain switching the ytterbium pump laser, typically operating with a repetition rate of 20 Hz and a duty cycle of 1%, resulting in a pulse width of 500 μs. The low-duty cycle was used for all experiments of this work to minimize thermal load. The output from the pump laser fiber (Liekki 12/250) was coupled through the mode-field adapter (insertion loss ~7%; ITF Labs, QC, Canada; Model No. MFA100C7131) to a single-mode fiber (HI1060, Corning), which included high-reflectivity Bragg mirrors (O/E land, LaSalle, Quebec). The power handling specification of the mode-field adapter was 100 W; while maintaining average power below 1.5 W, we observed no damage using pulses with up to 1-ms duration and 150-W peak power. Each FBG had >99% reflectivity with 2-nm bandwidth centered on each of the Stokes-shifted intermediate wavelengths as well as the output wavelength. This relay fiber was spliced to the Raman amplification medium. In the first configuration shown in Fig. 1(a), a standard fused silica fiber (HI1060; 200-m length) was used as a Raman gain medium. In the second configuration in Fig. 1(b), the Raman gain medium was replaced with a high-gain fiber with a filter function designed to inhibit the Stokes transitions to wavelengths >1500 nm (OFS Raman filter fiber; 100-m length). The third configuration used both fibers together in series (Fig. 1(c)).
Fig. 1. RFL configurations that were tested and numerically simulated. A single-stage Raman fiber medium was used with (a) Corning HI 1060 (200 m) and (b) OFS Raman filter fiber (100 m). A cascaded Raman medium of the two fibers was also tested, as shown in (c). Key splice points are indicated as a black dot; MFA: mode-field adapter; FBG: fiber Bragg gratings for wavelengths $\lambda_i$. Output coupling was nominally 96%, via a normal cleaved fiber–air interface.

3. Simulation method

For numerically simulating RFL output characteristics, we used a coupled-mode model including the pump beam ($P_0$) and the Stokes beams ($P_i$, $i = 1$ to $5$) in the following manner [14],

$$\frac{dP_n}{dz} = \left( -\alpha_0 - g_{0,1} \frac{\lambda_n}{\lambda_2} P_n^+ + P_n^- \right) P_0$$

(1)

$$\pm \frac{dP_i^\pm}{dz} = \left( -\alpha_i + g_{i,i+1} (P_i^+ + P_i^-) - g_{i,2} \frac{\lambda_i}{\lambda_2} (P_i^+ + P_i^-) \right) P_{i+1}^\pm$$

(2)

$$\pm \frac{dP_i^\pm}{dz} = \left( -\alpha_i + g_{i,i+1} (P_i^+ + P_i^-) - g_{i,2} \frac{\lambda_i}{\lambda_2} (P_i^+ + P_i^-) \right) P_{i+1}^\pm$$

(3)

$$\pm \frac{dP_5^\pm}{dz} = \left( -\alpha_5 + g_{5,6} (P_5^+ + P_5^-) \right) P_6^\pm$$

(4)

where $\alpha_i$ [km$^{-1}$] ($i = 0$ to 5) and $g_{j,i}$ [km$^{-1}$W$^{-1}$] ($j = 0$ to 4) represent attenuation and gain coefficients, respectively (Tables 1 and 2) [10,15,16]. The forward and the backward propagations are denoted by $+$ and $-$ signs. Equations (1)–(4) were represented using a discrete-step evolution along the longitudinal direction ($z$). For example, the forward-propagating power in Eq. (3) was written as

$$P_i^+ (n+1) = P_i^+ (n) +$$

$$\left\{ -\alpha_i + g_{i,i+1} (P_i^+ (n) + P_i^- (n)) - g_{i,2} \frac{\lambda_i}{\lambda_2} (P_i^+ (n) + P_i^- (n)) \right\} P_i^+ (n) \times \Delta z$$

(5)

where $\Delta z = L/n_z$ ($L$ is the fiber length, and $n_z$ is the total number of steps in the $z$-direction). Equations (1), (2), and (4) were represented similarly. In this model, the output powers at the
end of Raman gain medium, \( P_i^*(n = n_z) \), were obtained by evolving a set of initial conditions at \( n = 1 \) \( (P_i^*(1)) \) for \( i = 1 \sim 5 \). At each boundary of the Raman gain medium,

\[
P_i^*(1) = \frac{P_i^0}{R_{0,i}}
\]

(6)

\[
P_i^*(n_z) = P_i^*(n_z)R_{L,i}
\]

(7)

where \( R_{0,i} \) and \( R_{L,i} \) represent the reflectivities at the entrance and the exit of the Raman fiber. \( R_{0,i} \) is associated with the FBG reflectivity. At the exit, we used a non-zero reflectivity of \( R_{L,i} = 0.04 \) to represent the reflection from the fiber/air boundary of the normal cleaved output fiber. In order to solve this boundary-value problem with a discrete step evolution, we first chose a set of initial values \( (P_i^*(1)) \) and then calculated a set of Eqs. (5), obtaining the output values at the exit, \( P_i^*(n_z) \). This approach was iterated until Eq. (7) was satisfied within a minimal error range \( (\text{e.g. } P_i^*(n_z) - P_i^*(n_z) < 10^{-3}P_{in}) \). Equations (5)–(7) were used to obtain the RFL characteristics of the single-stage configuration without a mode-mismatching point (Fig. 1(a)). For the cascaded configuration (Fig. 1(c)), the Raman gain medium was separated into two regions from the spliced junction point \( (n = n_{junc}; \text{ i.e. } z = 200 \text{ m}) \): one with the HI1060 \( (n < n_{junc}) \) and the other with the filter fiber \( (n > n_{junc}) \). Equation (5) was used for \( n \neq n_{junc} \) with each attenuation and gain coefficients. At the junction of two Raman fibers \( (n = n_{junc}) \), an experimentally determined mode-mismatch loss of \( \delta_m = 1.4 \text{ dB} \) was multiplied at the right-hand side of Eq. (5) as following:

\[
P_i^*(n + 1) = \delta_m \times \left[ P_i^*(n) + \left( -\alpha_i + g_{i\rightarrow j+1}(P_{i+1}^*(n) + P_{i+1}^*(n)) - g_{i+1\rightarrow j}(P_{i+1}^*(n) + P_{i+1}^*(n)) \right) \delta_m \Delta z \right]
\]

(8)

For the backward-propagating beam \( (P_i^*) \), the same loss of \( \delta_m \) was applied to the backward transition. Equation (8) can be applied to RFL configurations with a mode-mismatching point. The single-stage Raman filter fiber system (Fig. 1(b)) was also characterized using Eq. (8), by setting the fiber-mismatching point into \( z = 1 \text{ m} \) and then calculating the longitudinal profile up to \( z = 101 \text{ m} \).

**Table 1. Attenuation Coefficients Used in Calculation**

| \( \alpha_i \) \( [\text{km}^{-1}] \) | \( \alpha_0 \) | \( \alpha_1 \) | \( \alpha_2 \) | \( \alpha_3 \) | \( \alpha_4 \) | \( \alpha_5 \) |
|---|---|---|---|---|---|
| Corning HI 1060 | 0.138 | 0.113 | 0.0929 | 0.0812 | 0.0814 | 0.0174 |
| OFS Raman Filter | 0.174 | 0.1517 | 0.1402 | 0.1296 | 0.13 | 0.0943 |

**Table 2. Gain Coefficients Used in Calculation**

| \( g_{i\rightarrow j} \) \( [\text{km}^{-1} \text{ W}^{-1}] \) | \( g_{0\rightarrow 1} \) | \( g_{1\rightarrow 2} \) | \( g_{2\rightarrow 3} \) | \( g_{3\rightarrow 4} \) | \( g_{4\rightarrow 5} \) |
|---|---|---|---|---|---|
| Corning HI 1060 | 1.2 | 1.1241 | 1.0819 | 1.0622 | 1.0503 |
| OFS Raman Filter | 5.14 | 4.51 | 3.946 | 3.432 | 2.967 |

**4. Results and discussion**

Figure 2 shows the total output power and the 5th-order Stokes power for the three laser configurations. The experimental results (solid lines) agree well with the corresponding numerical results (dashed). In the single-stage configuration using the standard fused silica fiber (HI1060) as a reference system (Fig. 2(a)), the total output power was 78.9 W (peak) for the input power of 121 W (peak). As compared with the other configurations, this system produced a relatively high total power because there was no mode-mismatch loss between the Raman gain fiber and the relay fiber including Bragg gratings. However, due to a limited Raman gain coefficient of HI1060 \( (1.2 \text{ km}^{-1} \text{W}^{-1} \text{ at 1120-nm wavelength [17]}) \), the Raman...
conversion process was not efficient, resulting in a low proportion of the 5th-order Stokes power among the total output: \( P_{1436} / P_{\text{out}} = 32.8\% \) for \( P_{\text{in}} = 121 \text{ W} \) (\( P_{1436} = 25.9 \text{ W} \)). Although the power at 1436 nm, corresponding to \( \sim 13 \text{ mJ/pulse} \), was sufficient for tissue coagulation, the unintended energy in the intermediate Stokes-shifted lines could be undesirable when considering potential damage to optical components in a fiber-optic delivery system.

In the second configuration, the gain medium was replaced with the Raman filter fiber with a higher gain of \( >5 \text{ km}^{-1}\text{W}^{-1} \) at 1090-nm wavelength and \( 2.55 \text{ km}^{-1}\text{W}^{-1} \) at 1450 nm [10]. While the overall output power was decreased, the proportion of the 5th-order beam was increased from 32.8% to 43.9% at the same power of \( P_{\text{in}} = 121 \text{ W} \) (\( P_{1436} = 23.9 \text{ W} \)). The total power reduction was caused mainly by a mode-mismatch loss (~1.4 dB). This loss could potentially be reduced using a fiber-taper adapter to properly accommodate the fiber dimension mismatch. For the single-stage configurations shown in Figs. 2(a) and 2(b), the Raman conversion efficiency (defined as \( P_{1436} / P_{\text{in}} \)) was 21.4% and 19.8%, respectively. The threshold to generate the 5th-order Stokes beam was \( P_{\text{in}} \sim 80 \text{ W} \).

Finally, in the third configuration using the cascade, the Raman conversion efficiency was enhanced to 35.1% (\( = P_{1436} / P_{\text{in}} \)) due to the increased Raman gain. The threshold for the 5th-order was reduced to ~30 W. More importantly, power was much more selectively converted to 1436 nm; power at 1436 nm comprised 90.1% of the total output (\( P_{1436} = 42.4 \text{ W} \)). This corresponds to a pulse energy of 21.2 mJ with an average power of 424 mW.

Laser output spectra were measured for selected pump powers (25.9, 74.2, and 121 W) and a fixed repetition rate of 20 Hz and duty cycle of 1%. Figure 3 shows normalized power amplitudes of each Stokes beams. For comparison, the simulated amplitudes (dashed bar) were superimposed on the corresponding experimental peaks (solid black). The progressive transition to higher orders is clear with the increased input power for all configurations: HI1060 (Figs. 3(a)–3(c)), Raman filter fiber (Figs. 3(d)–3(f)), and cascade (Figs. 3(g)–3(i)). Figure 3(c) shows that the HI1060 system produced the 5th-order Stokes beam at \( P_{\text{in}} = 121 \text{ W} \), but one half of the output power remained as the 3rd- and 4th-order intermediate states. Furthermore, a higher-order Stokes transition was observed with a small peak around 1540 nm (arrow), decreasing the conversion efficiency into 1436-nm emission. The higher-order transition was inhibited using the Raman filter fiber (\( P_{\text{in}} = 121 \text{ W} \) in Fig. 3(f)). The filter function was provided by a W-shaped index profile of the filter fiber to cut off light propagation at wavelengths longer than that of the 5th-order Stokes beam (3-dB roll-off at ~1490 nm) [12]. The cascaded configuration exhibited more efficient conversion due to the enhanced Raman amplification as well as the filter function. At \( P_{\text{in}} = 74.2 \text{ W} \) (Fig. 3(h)), the power proportion of the 5th order beam was 56.2% which is even higher than those of the single-stage systems at \( P_{\text{in}} = 121 \text{ W} \) (Figs. 3(c) and 3(f)). The conversion was further enhanced at \( P_{\text{in}} = 121 \text{ W} \) (Fig. 3(i)). Most of the power could be concentrated into the 5th order (\( P_{1436} / P_{\text{out}} = 90.1\% \)), leaving only ~9% at the 3rd order (1275 nm) and ~1% at the 4th order (1351 nm).
The relative ratio of the calculated Stokes beams in Fig. 3 shows close agreement with the experimental results for all configurations. However, in the HI1060 system, the Stokes transition to >1540 nm was not taken into account in the simulation process. The exclusion of the higher-order transition loss led to a relatively stronger 5th-order calculated peak than the experimental one (Fig. 3(c)). Whereas, the other systems (Figs. 3(f) and 3(i)) showed much better agreement with each experimental result at $P_{in} = 121$ W, as the higher-order transition is neither included in the experiment nor the simulation. For the simulation in Fig. 3, we assumed an equal splice loss of 0.04 dB at all of the fiber junctions. In experiment, however, slight variation would exist among the nodes (~0.1 dB). Moreover, our calculation model used an “effective” reflectivity for all FBGs representing the spectral leakage of the broadband Stokes beam outside of FBG reflection linewidth. The effective reflectivity is discussed in the following section in more detail.
Fig. 4. Longitudinal power profiles at $P_{in} = 121$ W (simulation): (a) HI1060 (200 m), (b) Raman filter fiber (100 m), and (c) Cascade (300 m). Solid and dashed lines denote the power profiles of forward- and backward-propagating beams, respectively. In (b), loss due to fiber mode-mismatch was included at the beginning position of the Raman filter fiber at $z \sim 1$ m (arrow). Accordingly, the end point of the longitudinal axis was slightly shifted beyond 100 m. In (c), the mismatching point was placed at the junction of two fibers ($z = 200$ m) (arrow). A net output power of each Stokes beam was obtained by $P_{i+} - P_{i-}$.

Using our simulation model, we examined the steady-state longitudinal power distribution within each Raman gain medium (Fig. 4). Only the results at $P_{in} = 121$ W are shown here. The HI1060-based system in Fig. 4(a) shows successive power transitions along the $z$-axis from the pump beam to the higher orders. In Fig. 4(b) for the single-stage Raman filter fiber, the power profile begins with steep reduction from 121 to 87.2 W (indicated by arrow), which is then followed by a smooth transition in a progressive manner. This is because we included the fiber-mismatch loss between the Raman filter fiber and the HI1060 relay fiber including the FBGs at the entrance in the calculation. The use of the Raman filter fiber led to more rapid power conversion (Fig. 4(b)). For example, the pump beam was completely depleted at $z \sim 25$ m with the Raman filter fiber, while this occurred at $z \sim 70$ m with the HI1060 in Fig. 4(a) despite two-fold longer fiber length. For the cascaded configuration, we placed the mode-mismatch point at the junction of two fibers (arrow; Fig. 4(c)). We note that the Raman conversion process at the entrance of Raman filter fiber ($z = 200$ m) already begins with significant amount of the 3rd-order Stokes beam. This is due to the HI1060 fiber serving as a pre-amplifying stage at $z < 200$ m. Furthermore, $P_{5+}$ was enhanced up to 10.2 W at the transition point of $z = 200$ m (after taking into account the mode-mismatch loss), as compared to $P_{3+} = 3.8$ W at the entrance of the single-stage Raman filter fiber in Fig. 4(b). The enhanced $P_{5+}$ works essentially as a stronger seed beam that facilitates the power conversion to the 5th-order output in the Raman filter fiber of the cascaded configuration.

Fig. 5. Pulsed waveforms of RFL at several repetition rates: (a) 20 Hz, (b) 50 Hz, and (c) 100 Hz. All waveforms have a fixed duty ratio of 1%.

Temporal waveforms produced by the RFL configuration of Fig. 1(c) were measured at the pulse repetition rates of 20, 50, and 100 Hz (Fig. 5), while maintaining a constant 1% duty cycle. The pulsed operation was obtained by modulating the pump diodes of the ytterbium laser. In Fig. 5, the average output power was fixed to 460 mW (46-W peak), resulting in the pulse energy of 23, 9.2, and 4.6 mJ, respectively. Each waveform has an approximately...
rectangular shape (500, 200, and 100 μs), containing ~90% power at 1436-nm wavelength. The pulse shape has a spike near the rising edge (shorter than 20 μs). This occurred in the pulse initiation process of the pump laser and was not associated with the Raman amplification.

In our free-run RFL configuration, the Stokes beams were selected by the high-reflectivity FBGs placed in the front stage; the ~4% feedback provided by the normal cleaved fiber output coupler was considered to be broadband. Under pump beam injection, the generated Stokes beam propagates in both forward- and backward directions. While the forward-propagating Stokes beam has a broad spectral width (>30 nm), the backward-propagating beam is reflected by an FBG and therefore spectrally filtered with 2-nm bandwidth. The reflected Stokes beam acts as a seed beam to boost the forward-propagating beam through the SRS process. In this regard, the high reflectivity of the FBGs is important to increase the overall Raman conversion efficiency. Once the Stokes beam power is sufficiently higher than the threshold for the next order, the next Stokes beam is generated, again propagating along both directions.

However, portions of the Stokes-shifted light that are outside of 2-nm bandwidth were lost. Apart from the high reflectivity within the designed bandwidth, an “effective” reflectivity for the broadband Stokes beam has been investigated to represent the spectral leakage experimentally [18–20] and numerically [21]. In our calculation, we adopted experimental values that were measured in a similar operation regime in terms of power (up to 180 W), type of fiber (Corning HI1060), and fiber length (30 m) [20]. The power dependence of the effective reflectivity was approximately

\[
R_{0,i} = \left(1 - 0.2 \left( \frac{P_{in}}{180} \right) \right) \times 10^{-\delta_i}
\]

where \(P_{in}\) is the input pump beam power to the Raman fiber, and \(\delta_i\) is the lumped loss for a round-trip pass through the FBGs that includes the insertion loss (\(\delta_{in}\)) and the splice loss (\(\delta_s\)). The factors of 0.2 and 180 were determined from [20]. The lumped losses were experimentally measured. For the FBG with a center wavelength of 1207, 1275, 1351, and 1436 nm, a single-pass insertion loss \(\delta_{in}\) was 0.05, 0.1, 0.3, and 0.34 dB, respectively (\(i = 2–5\)). The splice loss of 0.04 dB at each splicing point was used. Then, for the FBGs arranged in order from 1146 to 1436 nm (\(i = 1\) to 5), we obtained the accumulated losses for beam propagation through the multiple FBGs: \(\delta_i = 2.0, 1.8, 1.5, 0.8,\) and 0.08 dB for \(i = 1–5\). Using these values in Eq. (9), we obtained \(R_{0,i} = 0.29, 0.31, 0.33, 0.38,\) and 0.45 when \(P_{in} = 121\) W. For other input powers, the effective reflectivities were calculated similarly.

The current RFL configurations have two major loss mechanisms: FBG insertion loss and mode-mismatch loss. The insertion loss (\(\delta_{in}\)) of FBGs can be induced during the UV writing process for phase grating formation, leading to a broadband loss typically on the order of a few tenths of a dB [22,23] per grating and up to 1.5–2 dB for double pass through our configuration of five gratings. Mode mismatch loss occurs at the junction of the Raman filter fiber and the HI1060 fiber, and results in ~1.4 dB loss per single pass. If the RFL is prepared in a cavity-based design with Bragg mirrors at the end stage as well as the front, the Stokes beams would experience additional lumped losses and mode-mismatch losses by the end-stage FBGs. We confirmed that the total output power in the cavity configuration was decreased to less than one-half, although the fraction of power at 1436 nm was enhanced by the reduced threshold for the Stokes beams.

Based on our numerical simulation and experimental results, we concluded that 1436-nm performance may be further improved by integrating FBG reflectors directly into the Raman filter fiber. This configuration would eliminate the mode mismatch loss, thereby increasing the input pump power and reducing loss for the recirculating Raman-shifted orders. Simulation results for this configuration are shown in Fig. 6 and 2.6-fold enhancement in the 5th-order output power (Fig. 6(a); \(P_{1436} = 61.6\ W\) at \(P_{in} = 121\ W\)) as compared with the
mode-mismatch case (Fig. 2(b); \(P_{1436} = 23.9\) W at \(P_{in} = 121\) W). Also, the power proportion \((P_{1436}/P_{out})\) significantly increased from 43.9% to 70.2%. Figure 6(c) shows the longitudinal profile at \(P_{in} = 121\) W. This reveals the enhancement of \(P_5^+\) at the RFL entrance from 3.8 W (Fig. 4(b); mode-mismatch) to 12.5 W (Fig. 6(c); mode-match). Moreover, this involved a rapid build-up zone of the 5th-order beam over \(z = 70\)–100 m, which is similar with the one observed in Fig. 4(c) (\(z = 270\)–300 m).

![Fig. 6. Simulated RFL characteristics of a single-stage Raman filter fiber system (100 m) in which the FBGs are formed directly on the Raman fiber: (a) Total and 1436-nm output powers; (b) Normalized spectra of the Stokes beams at \(P_{in} = 121\) W; (c) A longitudinal power profile at \(P_{in} = 121\) W.](image)

We tested the laser configuration corresponding to the data of Fig. 3(i) for its ability to perform single-pulse tissue marking by coagulation. A sample of fresh porcine esophagus was prepared \(ex\) \(vivo\), making sure to maintain tissue hydration. The laser output was relayed by a two-axis galvanometric beam scanner and focused to a spot size of 37 \(\mu m\) (diameter at \(e^{-2}\) intensity). On the tissue so that individual pulses irradiated distinct spatial locations. Figure 7 represents data acquired using 900-\(\mu s\) pulses. Visible spots were obtained for pulse energies greater than \(~7\) mJ. Although laser irradiation in this example included power from all Raman orders, we note that the absorption coefficient for water, the dominant tissue chromophore in this case, is \(~31\) cm\(^{-1}\) at 1436 nm (only \(~4\) cm\(^{-1}\) at 1351 nm and \(~1\) cm\(^{-1}\) for all other orders [24]). In addition, the laser power at 1436 nm was roughly 90% of the total power. We estimate that the absorbed power density due to wavelengths below 1436 nm was less than 1% of the total.

![Fig. 7. A photograph of single-pulse coagulation spots generated on porcine esophagus (\(ex\) \(vivo\)). The pulse energy at 1436 nm corresponding to each row is denoted on the right; the pulse width was fixed to 900 \(\mu s\) for all cases.](image)
5. Summary

We demonstrated high-energy pulsed RFLs operating at 1436-nm wavelength using a pump wavelength of 1090 nm and designing 5-step Stokes transition systems. We generated microsecond pulses with >20 mJ/pulse, well above threshold for biological tissue coagulation and ablation. For systematic investigation of RFL performance, we compared the output characteristics using three RFL configurations, each of which has a different Raman gain medium: the standard fused silica fiber (Corning HI1060), Raman filter fiber (OFS), and a combination of both. Resulting output peak powers for these configurations were 25.9, 23.9, 42.4 W (13, 12, 21.2 mJ/pulse) at 1436 nm, respectively, for an input peak power of 121 W at the entrance of Raman fiber. The HI1060-based system produced significant power at wavelengths other than the desired 1436 nm (53 W), however, limiting the fractional 1436-nm output, $P_{1436}/P_{out}$, to 32.8%. The use of the Raman filter fiber significantly enhanced the conversion process to the 5th-order Stokes beam (1436 nm), resulting in $P_{1436}/P_{out}$ = 43.9% when used alone and 90.1% when preceded by a segment of HI1060. A numerical model, based on discrete step evolution of the pump and Stokes beams along the longitudinal axis of the Raman fiber, was found to be in close agreement with experimental observations. We also investigated the longitudinal power profile of each Raman fiber medium, using the same simulation approach. This revealed that the HI1060 fiber in the cascaded configuration works as an additional pre-amplifying stage, allowing enhancement of the 5th-order Stokes power in the connected Raman filter fiber. The RFL output characteristics were limited by two major loss mechanisms: the lumped insertion losses through the multiple FBGs (up to 2 dB) and the mode-mismatch loss between the filter fiber and the standard fiber (~1.4 dB). The latter loss may be further improved by using a tapered fiber adapter. Future work should additionally focus on optimizing the pump laser for low average-power, pulsed operation. The current pump, being designed for 400 W, cw operation, specifies the use of water cooling. In our studies, we operated the pump at the minimum duty cycle permissible by its software control, resulting in an average power of ~1 W, thereby greatly reducing thermal loading. Using the pulsed RFL, we demonstrated coagulation of porcine esophagus ex vivo. Visible spots were generated by single pulses having energies greater than ~7 mJ. The microsecond-pulsed RFL with a high energy of >20 mJ/pulse offers a new route not only for tissue coagulation and ablation by using 1.44-μm wavelength but also for efficient tissue marking and guided biopsy, when integrated with a fiber-optic imaging modality such as OFDI or confocal fluorescence endomicroscopy.

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