Characteristics of Erbium-Doped Superfluorescent Fiber Sources for Interferometric Sensor Applications

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Abstract—The characteristics of 1.55 \( \mu \text{m} \) Er-doped superfluorescent fiber sources (SFS's), intended for fiber-optic gyroscope (FOG) applications, are explored theoretically and experimentally. With proper selection of the source configuration, fiber length, pump wavelength, and temperature, we show that it is possible to meet the stringent requirements of the FOG, including a high output power, wide emission bandwidth, and extended spectral stability. Variations of the mean wavelength, spectral width, and output power of the SFS with fiber length, pump power, pump wavelength, and temperature are presented for representative sources pumped near 980 nm or 1.48 \( \mu \text{m} \), and are shown to be in good agreement with experimental results. The effects of a multimoded pump, erbium ion pair, and optical feedback are also assessed. This study indicates that the Er-doped SFS is an excellent candidate for the FOG and for other applications requiring spatial coherence and low temporal coherence.

I. INTRODUCTION

While many optical systems require narrow-band sources, a number of applications in interferometry and sensors require broad-band, high-power sources to reduce noise. In particular, the development of Er-doped superfluorescent fiber sources (SFS's) has been motivated by their potential use in fiber sensors such as the fiber-optic gyroscope (FOG) [1]-[10]. The requirements of sources for a navigational-grade FOG are listed in Table I, along with the goals of this research [11]-[17]. The FOG source must be broad band in order to minimize errors due to coherence effects. It must produce adequate power in a single spatial mode, which can be efficiently coupled into a single-mode fiber. Additionally, a navigational-grade FOG requires a mean source frequency which is stable with respect to temperature, feedback level, and the modulation frequencies produced by the FOG. This is essential because the FOG scale factor, which relates the detected signal to the rotation rate, is proportional to the mean frequency of the source spectrum. Since temperature control of a fiber to 0.1°C is easily achieved, a thermal coefficient less than 10 part per million (ppm) per degree Celsius of temperature change is required for the SFS to achieve a spectral stability of 1 ppm.

Because of its broad-band spectrum and compact size, the source of choice for the FOG has been the superluminescent diode (SLD) [18]-[21]. Unfortunately, most SLD's exhibit a mean wavelength variation on the order of 400 ppm/°C, which means that temperature control to 0.0025°C is required to meet the stability goal. Additionally, the power emitted by an SLD cannot be efficiently coupled into a single-mode fiber, and the lifetime of such devices is often inadequate for field use. For these reasons, broad-band Nd-doped SFS's at 1.06 \( \mu \text{m} \) were developed [22]-[23]. Such sources are inherently spectrally stable [24]-[25] and are easily coupled into the FOG fiber [26]. Recent demands for FOG sources which are insensitive to radiation-induced losses have motivated the use of Er-doped SFS's at 1.55 \( \mu \text{m} \), where the sensitivity of silica fibers is reduced compared to shorter wavelengths. The ability of the Er-doped SFS to meet the requirements of the FOG is assessed in this paper.

II. BACKGROUND

A. FOG Source Stability Requirements

To meet the stability requirements of the FOG, the mean frequency of a source must be stable not only with respect to the direct effects of temperature, but also with respect to other temperature-dependent parameters. Since spectra are most often measured with respect to wavelength, and since the magnitude of the fractional changes in mean frequency and mean wavelength are virtually identical for these sources, the data in this paper are presented in terms of mean wavelength coefficients in ppm/°C. To first order, the major components of the temperature dependence of the mean wavelength of an SFS are represented by

\[
\frac{d\lambda_{\text{source}}}{dT} = \frac{\partial \lambda_{\text{source}}}{\partial \lambda_{\text{pump}}} \frac{\partial P_{\text{pump}}}{dT} + \left( \frac{\partial \lambda_{\text{source}}}{\partial P_{\text{pump}}} \right) \frac{\partial P_{\text{pump}}}{dT}.
\]

(1)

The first term is due to the intrinsic dependence of the properties of the Er:silica medium on temperature. The second and third terms represent the mean wavelength variation with pump power and pump wavelength, respectively. The pump source of choice for the Er-doped SFS, the laser diode, typically produces a wavelength coefficient of about 400 ppm/°C and power variation on the order of -0.3 mW/°C.

Additionally, the mean wavelength of the source should change by less than 1 ppm as the FOG rotation rate varies over its useful range. Since any change with the rapid, large-amplitude feedback modulation of the FOG is undesirable, the source should be immune to high-frequency feedback modulation. In an open-loop FOG, which measures the actual...
This has been demonstrated with an Nd-doped SFS [33]. The usefulness of these configurations is discussed below.

The single-pass SFS, known as the fiber amplifier source (FAS), is more effective than 1 ppm for this 20% change. In a closed-loop FOG, a phase shift is introduced in the FOG loop to keep the measured signal constant. In this configuration, the dc feedback level is constant and dc feedback sensitivity is unimportant.

### B. SFS Design Parameters

The SFS designer can control the source spectrum, stability, and power through a choice of four parameters: pump power, pump wavelength, source configuration, and fiber length. Additionally, fiber design parameters such as dopant concentration, dopant profile, mode size, and codopants may also be varied within limits. The choice of pump wavelength and power is dictated by the available pump sources and by the available Er:silica absorption bands. While various pump wavelengths have been studied including 514 nm [27], 810 nm [28], 980 nm [29], and 1.48 μm [30], only the 980 nm and 1.48 μm pump bands are considered to be free from excited-state absorption (ESA) [31]-[32]. Additionally, both are now available as compact laser diodes. Both 980- and 1480-nm pumping are considered below.

Various configurations have been considered for the SFS/FOG system, depending on the presence of reflections from the fiber ends as well as the propagation direction of the pump wave relative to the propagation direction of the utilized source output. These are illustrated in bulk-optic form in Fig. 1. SFS's with two nonreflecting ends are single-pass devices [e.g., Fig. 1(a)], while those with a reflector at one end are double-pass devices [e.g., Fig. 1(b)]. The output from the pump end of the SFS is the backward signal, while the output from the opposite end is the forward signal. In a variation of the single-pass SFS, known as the fiber amplifier source (FAS) [Fig. 1(c)], the doped fiber acts not only as a backward-signal source, but also as an amplifier for the returning FOG signal. This has been demonstrated with an Nd-doped SFS [33]. The usefulness of these configurations is discussed below.

A diagram illustrating the relevant energy levels in Er:silica pumped at 980 nm, the wavelengths of their emission or absorption, and their approximate lifetimes [34]-[36] appears in Fig. 2. Pump power at 980 nm is absorbed to the 4$I_{11/2}$ state, which has a short lifetime of about 7 μs. The excited electron relaxes nonradiatively to the upper-laser state, which has a long lifetime of about 10 ms. The alternate pump transition at 1480 nm is also depicted in Fig. 2. Amplified spontaneous emission (ASE) near 1.55 μm occurs from the upper-laser state (4$I_{13/2}$) to the lower-laser state (4$I_{3/2}$), which is also the ground state. In most of this treatment, occupation of the 980 nm pump state is neglected because the lifetime of that state is short. However, when pumped near 980 nm, Er:silica is observed to radiate green light. The most likely process to produce this emission is ESA from the pump state (also called 980 nm upconversion), as shown in Fig. 2. In this process, pump absorption occurs from the pump state to a very short-lived state, which relaxes nonradiatively back to the pump state through intermediate states which emit in the visible and infrared. The strongest emission is observed near 545 nm from the $2H_{11/2}$ state (lifetime = 0.7 μs [35]-[36]). This process is included in the simulations only when noted below. The usual pump ESA process from the upper-laser state is assumed to be absent for 980 nm and 1.48 μm pumping.

Ion-ion interaction is a potential problem for fibers with moderate to high erbium concentrations. At high dopant levels, some Er$^{3+}$ ions, present in clustered or paired sites, decay rapidly to the ground state whenever two ions have been excited to the upper-laser state. These clustered ions absorb and waste both pump and ASE photons. However, they do not build up appreciable excited-state occupation when pumped at normal levels, and therefore do not provide gain. Even at
dopant levels of only a few hundred mole ppm of Er2O3, where large-scale clustering is not observed, evidence exists that a subset of the ions is paired and interacts rapidly via cooperative upconversion [37]-[40]. Paired ions reduce source efficiency by providing unsaturable absorption since only one ion in each pair can be excited at a time. The simulation of such pairs is discussed in Section III-C.

The design of broad-band Er-doped SFS is determined by the nature of the three-level Er:silica transition. Both the upper-laser state and ground state are Stark split manifolds with homogeneous and inhomogeneous broadening, and both are occupied according to Boltzmann statistics. Consequently, the absorption and emission cross sections are different functions of frequency and are temperature-dependent quantities. Simulation of such temperature dependencies will be discussed below.

The fiber used here was provided by AT&T, and its characteristics have been published [34]. According to this publication, the SiO2 core is doped with 1660 mole ppm of Er2O3 (about 9000 wt ppm Er3+ with an 11.4 ms lifetime) and is codoped with 8 mole percent Al2O3. Its core radius is 2.2 µm with an NA of 0.2. Discrepancies between the published cross sections and the fiber behavior were observed, both in low-power fluorescence spectra and in comparison of the results of SFS simulations and experiments. Plots of the measured maximum gain and maximum loss for this fiber are shown in Fig. 3. The gain was measured for a short fiber (<20 cm) pumped with about 300 mW at 980 nm, while the absorption was measured for the same short fiber unpowered, using a separate pumped Er-doped fiber as a fluorescent source. Using the theoretical overlap of 70% for the 1.55 µm signal with the dopant profile, assumed steplike, and using the published 1660 ppm doping level, the emission cross section at 1530 nm computed from these data would be only 2.95×10^-21 cm^2, which is low compared with published values [41]-[43]. Since the overlap, dopant level, and cross section appear as products in the governing equations (see Section III-B), these results suggest either a lower dopant level or a reduced overlap factor. Throughout this treatment, the dopant was set at 1040 mole ppm of Er2O3 (5600 wt ppm Er3+), the signal overlap was fixed at 70%, and the cross sections were computed from Fig. 3.

3. It should be noted that this method of computing cross sections from absorption and gain spectra differs from the usual spectroscopic methods. However, they produce perfect agreement between simulations and experiments for short fibers (by design) and good agreement for longer fibers.

C. Computation of Spectral Widths and Means

In this treatment, values for the mean wavelength and spectral width are presented. The mean wavelength is computed as a weighted average of the signal wavelengths, with power spectral density as the weighting factor, since this is how the FOG responds. For a power spectrum \( P(\lambda) \) measured at \( n \) equally spaced discrete wavelengths \( \lambda_i \), this is represented by the following summation:

\[
\bar{\lambda} = \frac{\sum_{i=1}^{n} P(\lambda_i) \cdot \lambda_i}{\sum_{i=1}^{n} P(\lambda_i)}.
\]

In the FOG, the output is measured by a square law detector. Since the error induced by various mechanisms is reduced in proportion to the spectral width of the source weighted by the square of the power, this might be the ideal way to compute the source width [44]-[45]. However, for the sake of simplicity, the width was computed with power as the weighting factor. If \( P_{\text{max}} \) is the maximum value of \( P(\lambda_i) \) across the spectrum, and if the \( n \) wavelengths represent widths \( \Delta \lambda_i \), this width is given:

\[
\Delta \lambda_{\text{source}} = \frac{\sum_{i=1}^{n} P(\lambda_i) \cdot \Delta \lambda_i}{P_{\text{max}}}.
\]

Such a weighted spectral width is necessary because definition of a 3 dB width is difficult for a spectrum with multiple peaks. This definition tends to underestimate by 5–10 nm the value that would be computed using a power squared weighting, and is therefore a conservative estimate. In our measurements, the spectrum was measured over a 100 nm range and was divided into 580 points, each representing a width of 0.172 nm. In our simulations, a 40 nm width was represented by ten wavelength regions, each simulating the power produced in a 4 nm bandwidth.
III. EXPERIMENTAL AND SIMULATION METHODS

A. Experimental Configuration

The setup used to measure the behavior of single-pass SFS’s appears in Fig. 4. Pump power was provided by an argon-pumped Ti:Sapphire laser which provided up to 600 mW of pump power, tunable from 950 to 995 nm. Pump power was coupled into the fiber using an 18× objective lens with a coupling efficiency of 47%. Both fiber ends were angle polished at 15° to prevent feedback from the fiber ends into the fiber core. Calculations indicate that, in theory, the objective lens provided about -57 dB of feedback. The SFS power was separated from the pump beam using a dichroic mirror. In measurements with controlled external feedback and for FAS configuration measurements, a beamsplitter was used to measure the backward signal while feedback was provided, at the same fiber end, using the optics shown in the dashed box of Fig. 4.

B. Simplified Simulation Method and Approximations

The behavior of Er-doped SFS’s is determined by the interaction between the population densities of the various energy levels and the optical signals. To analyze the problem rigorously, the radial form of the optical fields and their spectral content must be considered. While some authors have retained the radial dependence [46]-[47], this proved unnecessary for the purposes of this paper. The radial dependence can be accounted for by the use of effective signal and pump areas. To simulate the evolution of the SFS spectrum with the variation of design parameters, the cross-section dependence on wavelength was retained. This was accomplished by dividing the spectrum into ten regions and computing the evolution of the ASE in each region. The problem was then reduced to the consideration of 21 propagating optical waves: a unidirectional pump wave \( P_p(z) \) and two ASE waves for each spectral region; the forward-signal waves \( P_s^+(z, v_{s,i}) \) and the backward-signal waves \( P_s^-(z, v_{s,i}) \).

The rate equations and power evolution equations were derived for 980 nm and 1.48 \( \mu \)m pumping using the energy diagram of Fig. 2 and assuming homogeneous broadening. Complete equations appear in the Appendix. Except where noted, the 980 nm pump state was assumed to be unoccupied so that ESA from that state was ignored. Assuming that only one spatial pump mode (LP01) propagates, the equations for this simulation are

\[
\frac{dP_s^+(z, v_{s,i})}{dz} = \pm [\gamma_s(z, v_{s,i})P_s^+(z, v_{s,i})
+ \gamma_{es}(z, v_{s,i})2h\nu_{s,i} \left( \frac{\Delta
\nu_{bk}}{n} \right)]
\]  
\[
\frac{dP_p(z, v_p)}{dz} = -\gamma_p(z, v_p)P_p(z, v_p)
\]

with

\[
\gamma_s(z, v_{s,i}) = \frac{A_0}{A_{shp}}[\sigma_s(v_{s,i})N_{u}(z) - \sigma_a(v_{s,i})N_{l}(z)]
\]
\[
\gamma_{es}(z, v_{s,i}) = \frac{A_0}{A_{shp}}[\sigma_a(v_{s,i})N_{u}(z)]
\]
\[
\gamma_p(z, v_p) = \frac{A_0}{A_p} [\sigma_{pa}(v_p)N_{l}(z)]
\]  
for 980 nm pumping
\[
\gamma_p(z, v_p) = \frac{A_0}{A_p} [\sigma_{pa}(v_p)N_{l}(z) - \sigma_{pc}(v_p)N_{u}(z)]
\]  
for 1.48 \( \mu \)m pumping.

The occupations of the upper and lower laser states are given by (9a), (9b), and (10), shown at the bottom of the page, and \( P_s^+(z, v_{s,i}) = P_s^+(z, v_{s,i}) + P_s^-(z, v_{s,i}) \). The parameters for these equations, the equivalent areas, and the saturation intensities are defined in the Appendix.

The use of the equivalent area \( A_p \) to represent the overlap of the pump node with the doped core, and the equivalent area \( A_{shp} \) to represent the overlap of the signal mode with the doped core, was necessary to confine the spatial dependence.
to a single dimension. At low pump levels, the inversion in the core takes the spatial form as the pump beam (assuming little ASE saturation and a step-like dopant profile), while for high pump levels (and no ASE saturation), the inversion takes the form of the dopant profile. In these simulations, the high power value of the signal effective area \(A_{\text{signal}}\) was used. Calculations show that, for the fiber in this study, the low pump power effective area at 980 nm is 21.83 \(\mu m^2\), while the high pump power effective area is 22.69 \(\mu m^2\). The difference is minimal. It has also been assumed in this treatment that the pump wave is monochromatic. Additionally, the spontaneous emission input was taken as one photon per mode per unit homogeneous bandwidth. The assumption of an unoccupied pump state eliminated terms from (A12)-(A22)

### Table II

<table>
<thead>
<tr>
<th>Parameters Used in the Simulations</th>
<th>(N_d)</th>
<th>(4.27 \times 10^{19}) cm(^{-3}) (1040 mole ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber core area, (A_c)</td>
<td>15.21 (\mu m^2)</td>
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</tr>
<tr>
<td>Signal mode area, (A_{\text{signal}})</td>
<td>22.69 (\mu m^2)</td>
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</tr>
<tr>
<td>Pump mode area, (A_p)</td>
<td>17.23 (\mu m^2) (980 nm)</td>
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</tr>
<tr>
<td>Fluorescence lifetime, (t_\phi)</td>
<td>11 ns</td>
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<tr>
<td>Homogeneous linewidth, (\Delta\lambda_0)</td>
<td>40 nm</td>
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</tr>
<tr>
<td>ASE cross-sections: (\sigma_{\text{ASE}}(\nu_p))</td>
<td>4.72 (\times 10^{-21}) cm(^2)</td>
<td></td>
</tr>
<tr>
<td>(\sigma_{\text{ASE}}(\nu_s))</td>
<td>5.47 (\times 10^{-21}) cm(^2)</td>
<td></td>
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</tbody>
</table>

### Table III

<table>
<thead>
<tr>
<th>Parameters Used in Advanced Simulations</th>
<th>(7) (\mu s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump state lifetime, (\tau_p)</td>
<td>0.214 (\times 10^{19}) cm(^{-3}) (1/2 paired ions), (N_{\text{d,pa}})</td>
</tr>
<tr>
<td>Unsaturation ion conc. (N_{\text{d,pa}})</td>
<td>(1/2 ppm(0.05 (\times N_d))</td>
</tr>
<tr>
<td>LP(_{11}) pump mode area at 980 nm, (A_p)</td>
<td>26.04 (\mu m^2)</td>
</tr>
<tr>
<td>Pump emission cross-section, (\sigma_{\text{pump}}(\nu_p))</td>
<td>Pump absorption cross-section, (\sigma_{\text{pump}}(\nu_p))</td>
</tr>
<tr>
<td>Pump-state ESA cross-section, (\sigma_{\text{p-state}}(\nu_p))</td>
<td>5 (\times 10^{-21}) cm(^2)</td>
</tr>
<tr>
<td>Pump cross-section at 75(^\circ) C</td>
<td>Pump cross-sections at 25(^\circ) C</td>
</tr>
<tr>
<td>ASE cross-sections at 75(^\circ) C</td>
<td>(\sigma_{\text{ASE}}(\nu_s, I))</td>
</tr>
<tr>
<td>(\sigma_{\text{ASE}}(\nu_p, I))</td>
<td>(\sigma_{\text{ASE}}(\nu_s, I))</td>
</tr>
</tbody>
</table>

The equations in the Appendix were used for more advanced simulations to assess the significance of multimode pumping, pump upconversion, and ion–ion interactions. For a 980 nm pump, the fiber used here propagated two radially symmetric transverse pump modes. These modes are absorbed at different rates because the overlap of each mode with the dopant atoms is different. Simulation of this effect is complicated by the varying phase between the two pump modes. The radial dependence of pump power in the fiber can be a rapid function of the position along the fiber, so that pump saturation is difficult to model without computing full radial integrals at each position. However, the extreme cases of a pure LP\(_{01}\) or LP\(_{11}\) pump mode are treated by using different effective areas (see Appendix and Table III).

The equations in the Appendix also include ESA from the pump state at 980 nm (upconversion) described above. The cross section for this process was taken as 5 \(\times 10^{-21}\) cm\(^2\), a value chosen to be on the order of the other cross sections. The lifetime of the pump state is taken as 7 \(\mu s\), in agreement with published values for bulk Er:Silica [35]–[36]. This lifetime is the lower-laser state directly to the upper-laser state, at a wavelength for which the absorption cross section is larger than the emission cross section. Consequently, the lifetime of the pump state is the lifetime of the upper-laser state and pump reemission is significant. Equation (9b) indicates that when the 1.48 \(\mu m\) pump power is large and the ASE and pump wavelengths are similar.

### C. Advanced Simulation Methods

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long enough to allow as much as 5% occupation of the pump state in fiber regions with both high ASE and pump power levels. With the inclusion in the model of the occupation of the pump state, the pump reemission process must be included for 980 nm pumping. The cross section for this process was taken as equal to the pump absorption cross section for lack of better information.

Simulation of intrinsic thermal coefficients requires knowledge of all cross sections at two temperatures. These can be found either from theory or by measurement. Use of theory requires knowledge of the locations of levels within the Stark-split upper-laser and lower-laser manifolds, a scheme that correctly describes the strengths of transitions which contribute to different parts of the spectra, and a knowledge of Boltzmann statistics. In using such statistics, as temperature increases, levels near the bottom of each manifold become less occupied while levels near the top of each manifold become more occupied. Some schemes for the locations of the Ersilica transition levels have been proposed [48]-[50]. However, use of these schemes requires the density of states at different levels of the manifold, the widths of the manifolds, and the initial and final levels of the relevant transitions, which are not well-known quantities.

The gain and loss curves of Fig. 3 were converted to cross sections at 25°C (listed in Table II) by assuming the dopant level and overlap shown. Similar measurements at 75°C were accomplished by heavily pumping a short length of fiber and observing the change in gain at each wavelength as the fiber was heated between 25 and 75°C. The cross sections obtained at the ten simulation wavelengths by direct comparison of the emission at these two temperatures are shown in Table III. The mean wavelength of emission shifted toward longer wavelengths with temperature, which is only possible if emission near 1558 nm occurs from a higher energy level than emission near 1529 nm. This disagrees with one proposed scheme for this particular fiber [48]. Using Boltzmann statistics and assuming a uniform density of states in an upper-laser state manifold of width 300 cm⁻¹, approximate calculations indicate that the 1558 nm emission occurs from a level about 120 cm⁻¹ above the bottom of the manifold, while the 1529 nm emission occurs from a level about 30 cm⁻¹ above the bottom of the manifold. From the published data [48]-[50], all other spectral regions are probably due to multiple transitions and cannot be assigned a particular initial level.

Measurement of the absorption at 75°C was difficult due to thermal fluctuations in coupling and the need to use a short fiber to avoid depletion due to ASE saturation. However, if the values for the initial levels of emission at 1529 and 1558 nm are correct, and if the bottom of the upper-laser manifold is located at 6515 cm⁻¹ above the bottom of the lower-laser manifold [49]-[50], then the terminal levels are at 5 and 217 cm⁻¹ for the 1529 and 1558 nm transitions, respectively. If the lower-laser manifold is 500 cm⁻¹ wide [50] and the density of states is uniform, Boltzmann statistics give the change in cross sections from 25 to 75°C. The values computed in this manner for all ten ASE wavelengths are given in Table III. The mean wavelength of absorption shifts to longer wavelengths with a temperature increase (consistent with the results of measurement). This causes a shift in net gain towards shorter wavelengths. Hence, the shifts in ASE gain and absorption have opposite effects on the observed spectra. Based on simple measurements at 75°C, the pump absorption cross section for 980 nm was assumed to be constant with temperature.

The understanding of loss mechanisms in Ersilica is an ongoing research topic, and the simulation of these mechanisms depends upon the model used. The simulations presented here neglect background loss because the fiber is highly doped and therefore short. With lower dopant levels, a background loss term could be added to (6) and (8). To explain discrepancies between theoretical and experimental results reported in Section IV, a background loss of almost 400 dB/km needs to be assumed for this fiber, which is unreasonably high. A probable explanation for this discrepancy is that these fibers contain dopant ions with very short lifetimes that act as unsaturable absorbers [37]-[40]. The approach here will assume that these ions appear as pairs, and that such pairs can be approximated as one typical ion and one unsaturable absorber. This is strictly not quite true [39], but the discrepancy produced by this assumption as compared with a complete rate equation approach is small. The percentage of such absorbers was used as a fitting parameter to match the observed source output. For this fiber, the best fit was observed when assuming that paired ions constituted 10% (5% absorbers) of the dopant concentration. If large-size ion clusters are more realistic, they are still well represented by this pair approximation, assuming the number of pairs and the number of clustered ions are the same. For lack of better information, the absorption cross sections of paired ions were assumed to be the same as for the isolated erbium ions.

Advanced simulations were used to assess the accuracy of the approximations used above. Simulations that included radial dependence by incorporation of 20 radial rings produced insignificant differences in source characteristics. While the spectrum was divided into only ten wavelength regions, recent simulations with as many as 61 spectral regions indicate that ten regions are sufficient to accurately predict shifts in mean wavelength and power output (although they do not provide enough information to draw smooth spectra).

IV. RESULTS

A. Choice of SFS Configuration and Fiber Length

The usefulness of each configuration of Fig. 1 is limited by its efficiency and by its tendency to produce narrow-band resonant lasing in the presence of feedback. When the net feedback from both fiber ends equals the round-trip gain at some wavelength, the source is no longer an SFS and behavior in the FOG is adversely affected [24]. In this regard, double-pass devices are difficult to manage unless an isolator is used. Feedback levels of about -40 dB have been shown to initiate resonant lasing in such configurations [7]. On the other hand, the single-pass and FAS configurations are essentially immune to resonant lasing.

Plots of the length dependence of the output of different configurations are useful in clarifying the choice of configurations.
Simulations for this purpose were performed for various SFS configurations with 100 mW of pump power at 976 and 1475 nm. These wavelength choices will be explained below. A plot of the simulated output ASE power for these cases, assuming no ion pairing, is shown in Fig. 5. For the FAS configuration, the FOG was assumed to produce a 10% reflection and the plotted power is at the opposite fiber end. The fiber lengths are quite short due to the high dopant level used. To compare fibers with lower concentrations, the length can be scaled inversely with the concentration. Measured data for the fiber under consideration produced qualitative agreement with these plots, but lower output powers.

For short fibers, the gain is insufficient to amplify the spontaneous emission to high power levels. In the FAS and double-pass cases [Fig. 5(b) and (c)], the output increases rapidly with length to a maximum quantum conversion efficiency (photons out/photons in) on the order of 80-90% (depending on the exact pump power and wavelength considered). This translates to a power conversion efficiency from 50 to 57% for 976 nm pumping and from 76 to 85% for 1475 nm pumping. Beyond this optimal length, the output decreases gradually. Fiber lengths between 0.8 and 4.0 m are useful for 976 nm pumping, and lengths between 2.0 and 6.0 m are useful for 1475 nm pumping. These ranges will be narrowed later by other considerations. For single-pass operation [Fig. 5(a) and (d)], the forward-signal configuration is a is a poor candidate because its maximum quantum conversion efficiency is only about 30%. However, the backward signal continues to grow towards a maximum quantum conversion efficiency of 70-80% for long fibers. In this case, a lossy region exists at the forward fiber end which absorbs the forward ASE. However, some of the absorbed forward ASE is converted to backward ASE at longer wavelengths. For 980 nm pumping, fibers longer than 2.0 m are useful for this case, while for 1475 nm pumping, fibers longer than 3.5 m are useful.

The simulated mean wavelength of various configurations as a function of length is shown in Fig. 6 for 976- and 1475-nm pumping. The spectral width of such sources (3) is shown as a function of length in Fig. 7 for 976 nm pumping. The 1475 nm plots have been omitted in Fig. 7 for clarity and because they are surprisingly similar to the 976 nm plot. The form of these plots is explained by consideration of the interplay of the gain and loss spectra of Fig. 3. For fibers about 0.5 m long, the entire fiber is highly pumped in all cases so the spectrum (in dB) resembles the gain spectrum of Fig. 3. The mean wavelength is near 1530 nm and the width is between 5 and 10 nm. As the fiber length increases, signal saturation and pump depletion produce regions of the fiber with little inversion. Such conditions favor emission at longer wavelengths (near 1558 nm) where the gain coefficient exceeds the absorption coefficient. Hence, for all three configurations, the mean wavelength increases with increasing length above 0.5 m (see Fig. 6). The width reaches a maximum when the mean wavelength is about 1542 nm. This is the point at which the 1530 nm emission and the 1558 nm emission are nearly equal and the SFS spectrum is flattest. Beyond this point, the 1558 nm emission dominates and the spectrum narrows. This explanation will become clearer when spectra are presented in Section IV-B.

Fig. 7 suggests that for 976 nm pumping, fiber lengths of about 1.1, 1.3, and 3.2 m for the double-pass, FAS, and
backward-signal single-pass, respectively, are optimal, based strictly on spectral width. For 1475 nm pumping, these optimal lengths occur at 1.0, 1.2, and 2.1 m, respectively. However, spectral thermal stability must also be considered. Fig. 8 is a plot of the simulated intrinsic thermal shift in ASE mean wavelength as a function of length for both 976 and 1475 nm pumping. The FAS plots have been omitted because they essentially follow the double-pass plots. For double-pass devices, the optimal stability is obtained for double-pass devices either near 1.1 m or near 2.2 m where these plots cross 0. The second point is easier to use due to its more gradual crossing. For backward-signal, single-pass devices, 976 nm pumping produces larger thermal coefficients than for 1475 nm pumping, but lengths beyond 2.5 m are best in both cases. Generally, mean wavelengths above 1547 nm and maximum emission near 1558 nm correspond to greater thermal stability, but a reduced spectral width. This generalization is the direct result of the locations of the dominant transitions in the energy manifolds and Boltzmann statistics, as discussed in Section III-C above. The measured cross sections at 25°C (Table II) and 75°C (Table III) are nearly identical 1558 nm, but are substantially different near 1529 nm. Stable cross sections produce substantially ASE spectra.

B. Spectrum Evolution

Presentation of spectra for the myriad of SFS designs is impossible in this space. Some representative spectra have appeared in the literature [1], [27]. For short fibers pumped at 980 nm (typical for small-signal amplifier applications), the ASE spectrum looks like the gain spectrum of Fig. 3. However, for high-power SFS’s, ASE saturation produces spectra which result from a combination of the gain and loss spectra of Fig. 3. A few typical spectra for an Er-doped SFS are presented in Fig. 9. These were produced by pumping a 2.4 m single-pass SFS with 250 and 100 mW at 976 nm. The backward and forward spectra differ. The mean wavelength and width for the backward spectrum at 100 mW are 1543.9 and 21.7 nm, respectively, while for the forward spectrum they are 1553.3 and 17.9 nm, respectively. In the descriptions that follow, reference is made to the left peak and the right peak. These are visible in the spectra of Fig. 9; the left peak is near 1529 nm, while the right peak is near 1558 nm.

The signal emitted from either end of an Er-doped SFS is a complex function of pump power, fiber length, pump wavelength, and source configuration since these parameters affect the inversion of the medium. For conditions of complete inversion produced by a short single-pass SFS with a high pump power, both the forward and backward spectra are left-peaked. For a long single-pass SFS, a lossy unpumped region exists near the far end. Additionally, regions of signal saturation occur near the pump end (due to the backward signal) and beyond the position corresponding to the optimal length (due to the forward signal). The forward-signal begins as photons emitted near the pump end, while the backward-signal begins as photons emitted nearer the middle of the fiber where enough pump still remains to produce inversion. The forward spectrum in this case is a filtered version of the backward spectrum with the filter having attenuation (in dB) nearly proportional to the absorption spectrum (Fig. 3). Since the absorption is left-peaked, the forward spectrum has a reduced left peak, and is consequently more right-peaked than the backward spectrum (see Fig. 9). For double-pass operation, the output consists mostly of ASE photons which travel two passes through the fiber. In this case, the presence of ASE saturation near the output end of the fiber guarantees moderate inversion levels and the tendency towards right-peaked spectra.

Computer simulations provide the ability to study the evolution of the SFS power and spectrum along the fiber. The power in both the forward and backward signals at 1529 and 1558 nm and in the pump wave as a function of position for a 2.4 m fiber pumped with 100 mW at 976 nm are shown in Fig. 10. Pump power is absorbed rapidly near the input end because the high ASE power in this region rapidly consumes pump photons. Near 0.6 m from this end, pump absorption nearly ceases. The ASE power is low in this region, so the medium is highly inverted by small fractional absorption of pump power. Beyond 1.0 m, pump absorption is more rapid since high forward ASE power is present. The ASE power at 1529 and 1558 nm evolves differently (see Fig. 10). One way to estimate which wavelength dominates in the backward
direction is to integrate the gain for each wavelength over the length of fiber that produces gain greater than 0. At 1529 nm, the forward ASE continues to grow out to 1.25 m, while at 1558 nm, signal growth continues to 2.35 m. The simulation indicates that at 1529 nm, the gain is 40.05 dB from 0 to 1.25 m, while for 1558 nm, the gain is 39.98 dB from 0 to 2.35 m. The 1529 nm ASE experiences greater gain so the backward spectrum is somewhat left-peak. The forward ASE passes through a gain region and then a lossy region, so that the peak is estimated by integrating the gain for the entire length of fiber. In this case, the 1529 nm ASE experiences 25.24 dB of gain, while the 1558 nm ASE experiences 39.85 dB of gain. Hence, the forward-signal ASE is right-peak.

C. Power Output and Efficiency

Simulations (without loss mechanisms) have been used to estimate the maximum efficiency expected for each configuration for well-chosen fiber lengths. In Fig. 11, the predicted total SFS output power as a function of pump power for these cases is shown for 976 and 1475 nm pumping. The fiber lengths are 2.4 and 3.5 m for the backward-signal case and 1.2 and 2.4 m for the FAS and double-pass cases for 976 and 1475 nm pumping, respectively. In all single-pass cases, the feedback from the pump end was set at -57 dB, which is the computed value for our experimental setup (Fig. 4). All plots show the typical soft threshold of an SFS. The FAS and double-pass outputs approach a straight line for high power levels. The single-pass curves depart slightly from linearity because an increasing fraction of the power is emitted forward rather than backward as the pump power increases. For 976 nm pumping, the backward-signal single-pass threshold (taken as the projected x intercept of a straight line fit through the high power portion of the curve) and slope efficiency are 12 mW and 51.2%, respectively, while for 1475 nm pumping, they are 9.1 mW and 70%. For the FAS, the threshold and slope are 11.4 mW and 61% for 976 nm and 11.7 mW and 92% for 1475 nm. For the double-pass case, they are 9 mW and 62% for 976 nm and 9.6 mW and 95% for 1475 nm. These values are better than those measured for this fiber, but are expected to overestimate the efficiency since loss mechanism have been neglected. Recent experiments with lightly doped fibers have produced efficiencies approaching these theoretical figures.

When computed on a power basis, the 1475 nm pumped SFS’s are more efficient than the 976 nm pumped devices. This advantage is solely due to a favorable photon energy ratio. Considerable energy is wasted in multiphonon relaxation for 976 nm pumping. However, when computed on a photon basis, the 976 nm pumped devices are actually more efficient. This improvement is the result of a faster pump absorption rate at 976 nm, especially when the pump is single-moded. While the double-pass devices are more efficient than their single-pass counterparts, the advantage is not as sizeable as might be expected. The optimal single-pass devices are quite long so they benefit from the long interaction length and the absorption of forward photons to the benefit of the backward ASE.

The measured ASE power as a function of launched pump power for a 2.4 m piece of fiber for a 976 nm pump wavelength is shown in Fig. 12 for a single-pass device in both the backward and forward directions. The threshold pump power levels are 28 and 70 mW for the backward and forward signals, respectively, while the slope efficiencies are 38.1 and 12.8%, respectively. The measured data have been fitted by including 10% paired erbium ions, as described in Section II-C. As little as 10% pairing reduced the backward signal by 36% and the forward signal by 60% for 100 mW of pump power. Additionally, Fig. 12 includes a plot for the same backward-signal case simulated with the inclusion of pump ESA from the pump state at 980 nm. While this mechanism does produce an output reduction for high pump power levels, it does not properly account for the observed efficiency degradation. Instead, the reduction in output exhibits a squared dependence on pump intensity so it might become significant in high power lasers, especially for small mode sizes. Simulations with paired ions for 1480 nm pumping predicted similar source degradation. Double-pass and FAS configurations showed an even greater reduction in efficiency than the single-pass case.

The particular pump wavelengths used in Figs. 11 and 12 produced the greatest efficiencies for their respective pump bands. When measured for the 2.4 m fiber pumped at 965
nm, farther from the peak pump absorption wavelength, the backward-signal, single-pass ASE was reduced, but the forward ASE was enhanced. The threshold pump power levels for that case were 40 and 65 mW, with slope efficiencies of 26 and 20% for backward and forward signals, respectively. At both wavelengths, virtually all pump power was absorbed, and most pump photons produced signal photons emitted from either fiber end. Consequently, the sum of the slopes for pumping at 976 and 965 nm was similar. The total power produced was only reduced by 5–10% at 965 nm over the entire pump range tested.

Recent measurements for a 13.1 m piece of this fiber pumped at 976 nm with 272 mW of pump power have produced, upon careful optimization, 123 mW of backward signal power. This represents a 45.2% power conversion or a 72% conversion of pump photons to backward-signal photons. To produce such large backward conversion, it is necessary to minimize the pump end feedback and to carefully couple pump power into the fundamental pump mode. Coupling to other pump modes, which overlap poorly with the dopant ions, is similar to reducing the pump absorption rate, which reduces the backward-signal power. The conversion of over 50% of pump photons to backward-signal photons in a single-pass SFS is only possible in a three-level medium. For this configuration (without feedback), a four-level medium produces equal forward and backward ASE.

For all cases measured in these pump bands, the power output exceeded similar measurements at 514.5 nm, a pump wavelength which suffers from upper-laser-state ESA. The power output for a 3 m piece (near optimal length at 300 mW) of 300 ppm fiber configured in a forward-signal, double-pass configuration [Fig. 1(b)] pumped at 514.5 nm was reported previously [1]. The threshold and slope efficiency were 250 mW and 1.5%, respectively.

**D. Thermal Stability of SFS Output Spectra**

The thermal stability of Er-doped SFS’s depends on pump power, pump wavelength, fiber length, operating temperature, and configuration. Only three configurations are likely to be used for the FOG. In the forward-signal, double-pass configuration [Fig. 1(b)] and in the backward-signal, single-pass configuration [Fig. 1(a)], the stability of the source spectrum that passes through the FOG is the important quantity. However, for the FAS configuration [Fig. 1(c)], it is the stability of the forward spectrum that matters since this is the measured FOG signal. Since the evolution of the forward and backward spectra differ, the stability of each must be measured separately.

The intrinsic coefficient [first term of (1)] is governed by the relative importance of emission and absorption in each SFS configuration, and by the sign and magnitude of the spectral shift of these processes with temperature. A simple consideration of Boltzmann statistics suggests that, with an increase in temperature, higher levels of each manifold are occupied. This suggests that emission should shift to shorter wavelengths and absorption should shift to longer wavelengths with an increase in temperature. However, measurements have shown that the shift of both emission and absorption is towards longer wavelengths. Coefficients were measured, for a 2.4 m single-pass SFS, by placing the fiber in a temperature-controlled enclosure and cycling its temperature between 25 and 75°C, while maintaining a constant pump power. The measured thermal coefficients (in ppm/°C) for the backward signal for various pump power levels and pump wavelengths near 980 nm are shown in Fig. 13. The open points are for measurements with feedback, which will be discussed later. The coefficients are most positive for rapidly absorbed pump wavelengths (near 976 nm in this fiber) and for higher pump power levels. In all cases, the coefficients are between -2 and +10 ppm/°C, which is more than one order of magnitude improvement over semiconductor sources.

As was shown in Fig. 8, the FAS and double-pass configurations as well as all 1475 nm pumped devices can produce near zero intrinsic thermal coefficients with the proper fiber length. For these length values, the simulated thermal coefficients are shown in Fig. 14. The single-pass plot for 976 nm pumping agrees fairly well with the measured data of Fig. 13, as did curves for other pump wavelengths (not shown). All choices of optimal lengths for other configurations produced near zero

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**Fig. 12.** Measured output power (both directions) versus pump power for 2.4 m length (AT&T fiber) for single-pass SFS pumped at 976 nm. Results of simulations are shown for this case without loss mechanisms and with the two mechanisms considered.

**Fig. 13.** Measured intrinsic thermal coefficients versus pump power for single-pass, backward-signal SFS’s for various pump wavelengths near 980 nm. Plots for a few cases with feedback of -10 dB also appear as dashed lines.
intrinsic thermal coefficients at all pump power levels. Because these simulated values are critically dependent upon the ASE cross sections, which were only measured or computed to an estimated 10% accuracy, the error in the simulated coefficients is estimated to be as much as 5 ppm/°C (although they appear to be better). However, the trends observed with pump power variation and pump wavelength agree with measurements. Additionally, the thermal coefficients simulated for the 2.4 m single-pass SFS varied by as much as 3 ppm/°C for different pump modes. This may explain the variation of the measured coefficients by as much as 2 ppm/°C we observed from day to day.

The second term in (1), the pump wavelength dependence, was characterized by varying the pump wavelength (and thus the pump absorption) for a fixed pump power and temperature. The measured data for backward-signal SFS's appear in Fig. 15 for a 2.4 m fiber pumped at 300 mW, a 2.4 m fiber pumped at 100 mW, and a 1.1 m fiber pumped at 300 mW. Additionally, results are shown for a forward-signal, 2.4 m SFS pumped with 100 mW. For the top three curves, the solid lines are parabolic fits to simulation results. The backward-signal curves are nearly symmetric about the pump wavelength with the maximum absorption rate (near 976 nm for this fiber). The forward-signal dependence, representing the FAS output, is also symmetric about a wavelength near 976 nm, but the parabolic fits are inverted. Assuming the pump absorption cross section is a nearly symmetric function of pump wavelength about the peak at 976 nm, the symmetry of Fig. 15 suggests that two pump wavelengths with the same absorption rate produce nearly identical spectra for the same pump power. This is the expected behavior of a homogeneously broadened medium. It was not true for Nd: silica, which suffers from site-dependent pumping [51]. The symmetry about the peak pump absorption wavelength has been observed for other configurations, with reduced curvature for the FAS and double-pass devices.

Operation at the minimum of Fig. 15 produces a zero-magnitude first-order pump wavelength dependence. Inclusion of a second-order term shows that, for the 2.4 m fiber pumped with 300 mW at 976 nm, temperature control to 0.6°C would be required for a 1 ppm maximum variation (assuming 400 ppm/°C pump variation). This requirement is less stringent than those imposed by the intrinsic variation (Fig. 13). At all wavelengths more than 1 nm from the peak absorption wavelength, the pump-wavelength-dependent term produces the largest contribution to the net thermal coefficient of the SFS. In fact, at 962 nm, this term would contribute more than −100 ppm/°C.

Because 1475 nm pumping occurs in the wings of the ASE manifold, it is impractical to operate at the peak pump absorption wavelength. The simulated mean wavelength dependence on pump wavelength for a 3 m long single-pass Er-doped SFS for three pump power levels near 1475 nm is shown in Fig. 16. Fortunately, just as is the case for 976 nm pumping, this dependence has a local minimum at 1475 nm for the backward signal. This wavelength is also the wavelength that produces the maximum power output. Operation at this point would yield a 0 ppm/°C contribution to the net source thermal coefficient. Also, the curvature at this point is less than the curvature around 976 nm, so that the second-order term is also smaller. In the wings of the 50 mW curve near 1445 nm, the slope is about −0.067 nm/nm which, when combined with the typical pump diode dependence, would yield a contribution to the mean wavelength thermal coefficient of −26.7 ppm/°C. This is the largest contribution and illustrates the need to operate near 1475 nm.

The third term of (1), the pump power dependence, was measured by varying the pump power for a fixed pump wavelength and temperature. This appears in Fig. 17 for a 2.4 m single-pass SFS for various pump wavelengths near 980 nm in both the forward and backward directions. The fits were generated by the simulation and are in general agreement with the measured data. In most cases, an increase in pump power produced a decrease in mean wavelength with a slope as large as −93 ppm/mW. However, when pumping with 50 mW near 976 nm, the slope is approximately zero. Since pump power control to within 1 mW is easy,
operation near enough to this point to produce a slope less than 1 ppm/mW is an excellent choice. For a typical laser diode, the contribution from the pump-power-dependent term of (1) is less than 10 ppm/°C. The disagreement between measurements and simulations observed in Fig. 17 for spectra with mean wavelengths above 1556 nm is due to the lack of enough simulated spectral information above 1555 nm. The disagreement of about 1 nm for 970 nm pumping might be the result of inaccuracy in the value of the pump absorption cross section used in the simulation or measurement error.

For other configurations and for 1475 nm pumping, the simulated mean wavelength dependence on pump power is shown in Fig. 18. The dependence for the 1475 nm pumped single-pass SFS is similar to that of Fig. 17 for 976 nm pumping, except for the lack of a local maximum near 50 mW. The slope for the backward-signal 1475 nm pumped SFS is about −0.2 ppm/mW. When combined with the typical diode thermal dependence (−0.3 mW/°C), this would give a manageable 1.5 ppm/°C contribution to the mean wavelength thermal dependence. Fig. 18 illustrates the reason for the choice of the 2.4 m fiber length for the 976 nm pumped double-pass SFS as opposed to 1.2 m where the efficiency is maximum. The 1.2 m fiber produces a steeper slope for reasonable pump power levels below 50 mW. In fact, all devices with mean wavelengths above 1555 nm are apparently insensitive to variations in pump power level. The price paid for this stability is a reduction in spectral width. All of these devices produce right-peaked spectra with widths between 15 and 20 nm, while widths near 30 nm are possible for twin-peaked spectra.

E. Effects of Higher Order Pump Modes

The presence of multiple pump modes at 980 nm can be detrimental to the stability of the Er-doped SFS because the overlap of each pump mode with the dopant profile is different and their absorption rates differ. Almost all Er-doped fibers are single-moded near 1.48 μm so this concern disappears for 1.48 μm pumping. Coupling to the second pump mode at 980 nm is zero for a centered symmetrical pump beam, but can be substantial for off-center coupling. Simulations of this effect were performed as described in Section III-C using the computed effective areas (assuming a step-like dopant profile) given in Table III. The case of 50% coupling to each mode is difficult to simulate because the intensity pattern of the pump depends on the phase relationship between the two modes. For the sake of computation, the pump modes were assumed to propagate independently and to saturate the medium in proportion to their (different) effective areas. The results of simulations of the mean wavelength for 2.4 m long SFS's pumped at 976 nm is shown in Fig. 19 for different coupling conditions. It is noted that the power output is only slightly affected by the pump mode. However, the effect on the mean wavelength of the source is significant for the single-pass device. At 100 mW, the backward-signal mean wavelength changes by 1400 ppm for a shift from the LP_{11} to the LP_{11} pump mode. On the other hand, the single-pass SFS is insensitive because photons pass through the entire fiber, which still has nearly the same net inversion, although redistributed along the fiber. Hence, three solutions are possible: double-pass operation, the use of fibers which are single-moded at 980 nm, or pumping near 1.48 μm.
Fig. 19. Simulated SFS mean wavelength versus pump power at 976 nm for (a) backward-signal, single-pass, 2.4 m, and (b) forward-signal, double-pass, 2.4 m for various coupling conditions to the LP01 and LP11 pump modes of this fiber.

F. Effects of Feedback

While the results above were measured and simulated with little feedback, the FOG provides feedback and may alter the characteristics of the FOG. Although an isolator is a possible solution to this problem for a single-pass device and a necessity for double-pass operation, it is costly and complicates the system. A typical SFS produces between −30 and −10 dB of feedback. To study feedback effects, the optics in the dashed region of Fig. 4 were added to the backward-signal, single-pass SFS. Calibration measurements indicated that with this system, a maximum of 12.5% of the backward-signal power emitted by the source could be returned to the fiber mode. However, the system behaved (compared to the modeling presented below) like it produced about 7% maximum feedback. The discrepancy is most likely the result of aberrations in the objectives, distortion introduced by the beamsplitters or mirrors, or poor modal overlap (such effects were not included in the calibration). Attenuators were added in the feedback path to vary the level of feedback.

Because the lifetime of the upper-laser state is so long in Er:silica, it is not expected to respond to high-frequency-modulated feedback. This was confirmed by adding an acousto-optic modulator to the feedback system of Fig. 4. The response of the backward-signal power to feedback was observed to roll off at 10 dB/decade like a single-pole system with a pole slightly below 1 kHz. At a frequency of 100 kHz, typical of the modulation frequency of an FOG, the response was down by 25 dB. For frequencies below 100 Hz, the medium was able to respond fully to the modulation [7]. The measured power produced by a 2.4 m SFS in the backward and forward directions as a function of the feedback level for 250 mW of pump power at 976 nm is plotted in Fig. 20, along with simulated results. The simulation included 10% ion pairing in order to accurately predict power levels. The simulated and measured curves are similar in form, but are shifted with respect to each other, probably due to a calibration error in the feedback system. For the case illustrated, a feedback level of about 1% (−20 dB) reduced the measured backward power from about 80 mW to less than 10 mW, while increasing the forward power from 20 mW to over 60 mW. This favors the FAS configuration by enhancing the useful output or, equivalently, reducing the required pump power. On the other hand, it hinders the backward-signal source by reducing the available source power.

The spectrum of the SFS is also altered by the presence of feedback. Generally, the effect is to favor the right peak in both the forward-signal and backward-signal directions with a feedback increase. A plot of the measured and simulated mean wavelength as a function of feedback for the 2.4 m SFS pumped with 250 mW at 976 nm appears in Fig. 21 for both directions. The form of these curves is typical, and was observed to vary slowly with pump power, pump wavelength, and fiber length. Unfortunately, for feedback levels likely to exist in the FOG, the mean wavelength is a rapid function of feedback. In an open-loop FOG, the feedback level is expected to vary by 20% (about 1 dB) with rotation rate. This would cause on the order of 100 ppm of variation in mean wavelength when operating above −30 dB of feedback. Only when the feedback is low (requiring the use of an isolator) is the dependence reduced. Unfortunately, this is not possible for the FAS configuration, which requires the amplified FOG signal to be larger than the forward-traveling ASE. In a closed-loop FOG, the dc feedback remains constant (high frequency modulation is still present) so the feedback dependence is not critical. In this case, for a backward-signal source, the feedback must be kept low to maintain a high backward-signal level (see Fig. 20). If, on the other hand, an FAS for a closed-loop FOG is desired, the feedback level must be high since this favors the forward signal.

The intrinsic stability of the spectrum with temperature was measured for a few sets of conditions with the maximum feedback level (nominally 12.5%), and these points appear in Fig. 13 for the backward-signal. These coefficients are less than 10 ppm/°C and are more negative with feedback than without feedback. With the maximum feedback level, the pump wavelength dependence for this same configuration pumped at 100 mW was found to follow the same form as in Fig. 17, but it was shifted toward longer wavelengths. The pump wavelength dependence with feedback was still
symmetric about the peak pump absorption wavelength at 976 nm as in Fig. 15, but the curvature was reduced. This bodes well for the use of the FAS and double-pass devices which operate with high feedback levels.

G. Fiber Optimization

The results presented have been for a heavily doped fiber. In general, these results are valid for lightly doped fibers of similar composition, assuming the length is scaled by the dopant concentration. The only difference is that, as the dopant level decreases, the source efficiency usually increases. However, according to the simulations, the basic spectral dependences still hold. To increase the lifetime of pump diodes in real systems, optimization of the fiber is necessary to reduce the required pump power. It has been shown that the efficiency of a backward-signal ASE source is directly correlated to the efficiency of a power amplifier made from the same fiber [52]. Hence, the same fiber optimization issues apply to the SFS fiber as apply to amplifier fibers. Theoretical analyses based on simulations suggest that tight dopant confinement and high NA small-core fibers should produce greater amplifier efficiencies. In general, smaller mode areas and tightly confined dopant reduce the saturation intensities which should reduce the threshold power of sources. Simulations of ASE sources performed by changing the equivalent mode areas and core area have shown that these steps should reduce the threshold power, but have little effect on the slope efficiency.

Unfortunately, Er-doped fiber optimization is not so simple. As dopant confinement increases, the concentration in the doped region increases, and so does erbium ion pairing and clustering. Such loss mechanisms reduce the slope efficiency of ASE sources [39]. If the dopant level is decreased too much, background loss may become significant. To the authors' knowledge, the pair concentration as a function of erbium concentration and codopant type has not appeared in the literature. The trend in recent fiber production has been towards concentrations a factor of 10-20 times lower than the fiber used here. Even so, these fibers do not quite produce the efficiencies predicted in Fig. 11. Work still remains to find the ideal host and concentration levels for optimum fibers.

V. Summary

Various Er-doped SFS configurations are useful, depending on the requirements of the application. Certain choices of pump wavelength, pump power, and fiber length are essential for the FOG. The choices, advantages, and disadvantages of each of the three configurations are summarized in Table IV. Design tradeoffs suggested by this table are best illustrated by examples. To guard against resonant lasing, a backward-signal single-pass SFS made from 2.5 m of fiber pumped by 50 mW near 976 nm is ideal. A good isolator is useful in this case to produce a high power level and to reduce susceptibility to feedback variation in an open-loop configuration. Assuming an efficient fiber, simulations suggest that this source could produce 18 mW of power (measured 8 mW for this fiber) with a 23 nm bandwidth. Its intrinsic thermal coefficient is estimated at about +6 ppm/°C with a simulated pump-power-dependent thermal coefficient of -4.3 ppm/°C (measured near 0 ppm/°C). Shifting the pump wavelength slightly above 976 nm to give a +4.3 ppm/°C would cancel all diode dependences. Unfortunately, simulations predict a 40 ppm variation of mean wavelength with a 20% feedback change for 45 dB of isolation. A reduction of the feedback level to -60 dB would reduce this figure, but the safest solution is a closed-loop FOG with a constant dc feedback level.

To increase the detected power (or decrease the pump power), an FAS source is a good choice. The length of the fiber could be shorter than the previous case to optimize the forward spectral width and/or output power. A length of about 1.5 m would produce a broad forward spectrum when pumped with 50 mW near 976 nm. Typically, the feedback level is about 1% for a low-loss FOG, so this case was considered. Simulations predict almost 20 mW of output power and a 24 nm bandwidth in the forward direction. The intrinsic thermal...
coefficient is estimated at $-3 \text{ ppm/}^\circ\text{C}$ with a simulated pump power dependence of $+16 \text{ ppm/}^\circ\text{C}$. This could be cancelled by operation at a wavelength below 976 nm. Unfortunately, the feedback susceptibility is large, producing as much as 300 ppm variation in mean for an open-loop FOG. Closed-loop operation would be essential for the FAS. Additionally, it would be difficult to use a single FAS as a source for three FOG axes since crosstalk might occur.

In short, all three configurations can meet the requirements listed in Table I. They can produce adequate power when pumped by typical single-stripe diodes. Threshold pump levels between 5 and 20 mW and quantum slope efficiencies between 50 and 95% are attainable with efficient fibers. Double-pass and FAS configurations are more efficient, and the FAS device benefits from the output being an amplified version of the FOG output. All configurations produce spectral bandwidths between 10 and 30 nm (by our conservative definition) and better thermal stability than their semiconductor counterparts. Intrinsic coefficients less than 10 ppm/$^\circ\text{C}$ are expected, with the FAS and double-pass devices producing near zero coefficients. All pump power and pump wavelength dependences are manageable and optimal design choices exist. The greatest distinctions between the configurations are in the areas of feedback sensitivity, pump mode sensitivity, and susceptibility to resonant lasing. The backward-signal single-pass device must either be isolated or operate with a closed-loop FOG to remain spectrally stable with feedback. The requirement for isolation is even greater for the double-pass device where resonant lasing is always a threat. As discussed above, the FAS configuration cannot be isolated, but resonant lasing is easily avoided. In general, the FAS and double-pass devices are spectrally insensitive to pump mode coupling, pump power level, and pump wavelength.

Application of the above design method to pumping near 1480 nm is straightforward, and similar results are expected. Operation at 1475 nm produces the same wavelength stability advantages as does operation at 976 nm. Both the 980 nm and 1.48 $\mu$m pump bands produce excellent SFS characteristics. Some distinctions between these pump bands are summarized in Table V. Efficiency can be compared two ways, depending on whether electrical or optical conversion is the issue since typical 980 nm diodes are more efficient than 1.48 $\mu$m diodes. 980 nm pumping requires shorter fibers and can produce broader spectra. However, 1.48 $\mu$m pumping produces less pump wavelength spectral dependence and easy single-moded pump operation. Both pump bands produce excellent SFS characteristics for optimized design choices.

VI. CONCLUSIONS

We have demonstrated that, with carefully chosen design parameters, the Er-doped SFS can produce high source power (>10 mW) for single-stripe diode pumping, broad spectra (width > 25 nm), and a stable mean wavelength (<1 ppm variation with attainable temperature control). The backward-signal, single-pass configuration has the clear advantage of low susceptibility to resonant lasing due to feedback from the FOG. Double-pass configurations may also be considered because of their lower pump power requirements near the threshold power region and greater spectral stability. However, such devices are susceptible to resonant lasing and resultant narrow-band operation. The FAS configuration offers the best combination of characteristics because of its reduced pump power requirement, its excellent spectral stability, and its resistance to resonant lasing.

Simulations have clarified some of the issues involved in producing the highest power, most stable Er-doped SFS’s. The use of a pump wavelength with little or no pump ESA, such as 980 nm or 1.48 $\mu$m, is essential for producing maximum efficiency. Furthermore, the data clearly show that use of a pump wavelength which is single-mode in the fiber increases the stability of the SFS mean wavelength by eliminating the need for careful modal coupling control. Additionally, careful processing of the fiber itself is essential since even small fractional amounts of ion pairing can significantly reduce the ASE power output. Er-doped fibers require less pump than their Nd-doped fiber counterparts and produce broader bandwidths. The Er-doped SFS is a likely candidate to replace the SLD for sensor applications because of its thermal stability (an order of magnitude better than SLD’s), high power output, short temporal coherence length, high degree of spatial coherence, and operation at 1.55 $\mu$m.

VII. APPENDIX
EQUATIONS FOR ADVANCED SIMULATIONS

In simplified treatments of Er-doped amplifiers, only the upper-laser state and the ground state are assumed to be occupied. Pump and signal excited-state absorption (ESA) from the pump state or from the upper-laser state are neglected because the cross-sections for these processes are small or the occupation of the absorbing state is negligible. While pump
ESA from the upper-laser state is deemed negligible in this treatment for 980 and 1480 nm pumping, pump ESA from the pump state is included for 980 nm pumping because this process may be significant in high power ASE sources. It is assumed that most ions excited via ESA return rapidly to the pump state. Additionally, the propagation of two spatially symmetric pump modes at 980 nm has been included to assess the need for single-moded fibers at 980 nm. Furthermore, absorption due to the presence of clustered or paired erbium ions has been included in the simplest fashion.

Under the assumption of homogeneous broadening, it is convenient to consider the entire population of a given state, and to represent the interband transitions by frequency-dependent absorption cross sections. Assuming that the dopant concentration is axially independent and that the occupation of other excited states is negligible, we write

\[ N_d \xi(r) = N_{l}(r, \theta, z) + N_{u}(r, \theta, z) + N_p(r, \theta, z) \]  

where

- \( N_d \equiv \) average dopant concentration of erbium ions in unclustered sites
- \( \xi(r) = \) normalized transverse dopant distribution \((\int \int \xi(r) r \, dr \, d\theta = 1)\)
- \( N_{l}(r, \theta, z) \equiv \) lower-laser state (ground state) population density
- \( N_{u}(r, \theta, z) \equiv \) upper-laser state population density
- \( N_p(r, \theta, z) \equiv \) pump state population density.

The rate equations describing the time evolution of the various population densities are derived using standard laser theory [53]. The equations include integrals of the dopant profile and various power spectral densities over two transverse dimensions and frequency. Despite the assumed axial independence of the dopant, the population densities do have axial as well as transverse dependences which are not separable. The signal spatial distribution is assumed to be the lowest z-independent eigenmode. The pump spatial distribution is a more complex issue because the pump may propagate in more than one (two radially symmetric modes at 980 nm in our fiber) z-independent eigenmodes. For simplicity, this treatment assumes that the pump modes can be propagated separately on an intensity basis, each overlapping differently with the dopant atoms. If the beat length of the fiber is short, this approximation is reasonable but not rigorous.

Point-by-point integration over transverse and axial dimensions was eliminated by assuming that these integrals are independent of position and can be approximated by effective areas. Inclusion of summations over radial variables is not difficult, but proved time consuming and unnecessary. If the core has radius \( r_c \), its area \( A_0 = \pi r_c^2 \). Then, if we define

\[ \phi_{p, 0}(r, \theta) \equiv \] normalized 0, 0 pump mode distribution \((\int \phi_{p, 0}(r, \theta) r \, dr \, d\theta = 1)\)

\[ \phi_p(r, \theta) \equiv \] normalized signal distribution \((\int \phi_p(r, \theta) r \, dr \, d\theta = 1)\)

the effective areas for the first two pump modes are

\[ A_{p0}^{-1} = \int \int \xi(r) \phi_{p, 0}(r, \theta) r \, dr \, d\theta \]  

(A2)

\[ A_{p1}^{-1} = \int \int \xi(r) \phi_{p, 1}(r, \theta) r \, dr \, d\theta \]  

(A3)

while the signal wave effective area is

\[ A_s^{-1} = \int \int \xi(r) \phi_s(r, \theta) r \, dr \, d\theta. \]  

(A4)

The equivalent signal area of (A4) is correct if the pump power is high enough to approximate the ions as inverted uniformly in the radial direction. For low pump regions, the equivalent area of the signal beam depends on the pump profile and is better represented by

\[ A_{s0}^{-1} = \int \int \xi(r) \phi_{s, 0}(r, \theta) \phi_p(r, \theta) r \, dr \, d\theta. \]  

(A5)

Assuming a first-order pump mode and using the fiber parameters for a typical fiber, the difference between the definitions of effective areas is often slight. In what follows, the high power equation (A4) is used uniformly since the SFS is a high power device.

It is now possible to write propagation equations for forward and backward ASE waves and for two pump waves representing two pump eigenmodes. For this, we define

- \( n \equiv \) number of ASE wavelengths simulated
- \( v_{s, j} \equiv \) signal frequency for \( j \)th simulated spectral region
- \( \omega_p \equiv \) pump frequency (assumed to be monochromatic)
- \( \sigma_{ps}(\omega_p) \equiv \) pump ground-state absorption cross section
- \( \sigma_{pe}(\omega_p) \equiv \) pump emission cross section (from pump state at 980 nm, from upper-laser state at 1480 nm)
- \( \sigma_{a}(\omega_s) \equiv \) signal ground-state absorption cross section
- \( \sigma_{e}(\omega_s) \equiv \) pump excited-state absorption cross section from pump state (at 980 nm only)
- \( \tau_u \equiv \) upper laser-state lifetime
- \( \tau_p \equiv \) pump-state lifetime (for 980 nm only)
- \( N_{ab}(r, \theta, z) \equiv \) number density of erbium ions acting as unsaturable absorbers with very short lifetimes (either half of paired ions or all of clustered ions).
Using these parameters, it is helpful to define the following saturation intensities:

\[ I_{s_{\text{sat}}}(v_{s}, i) = \frac{\hbar v_{s}}{\tau_{u}[\sigma_{e}(v_{s}, i) + \sigma_{a}(v_{s}, i)]} \]  
(A6)

\[ I_{p_{\text{sat}}}(v_{p}) = \frac{\hbar v_{p}}{\tau_{u}\sigma_{p_{u}}(v_{p})} \]  
(A7)

\[ I_{p_{\text{sat}}}(v_{p}) = \frac{\hbar v_{p}}{\tau_{u}\sigma_{p_{u}}(v_{p})} \]  
(A8)

\[ I_{p_{\text{sat}}}(v_{p}) = \frac{\hbar v_{p}}{\tau_{u}\sigma_{p_{u}}(v_{p})} \]  
(A9)

\[ I_{u_{\text{sat}}}(v_{p}) = \frac{\hbar v_{p}}{\tau_{u}\sigma_{p_{u}}(v_{p})} \]  
(A10)

\[ I_{u_{\text{sat}}}(v_{p}) = \frac{\hbar v_{p}}{\tau_{u}\sigma_{p_{u}}(v_{p})} \]  
(A11)

For the sake of computation, a small number of ASE waves at frequencies across the 1.55 \( \mu \)m spectrum are propagated, with each representing a spectral width of \( \Delta v_{p} n \). The propagation equations for the ASE and pump waves are

\[ \frac{dP_{s}(z, v_{s}, i)}{dz} = \pm \left[ \gamma_{s}(z, v_{s}, i)P_{s}(z, v_{s}, i) + \gamma_{cs}(z, v_{s}, i)2hv_{s} \left( \frac{\Delta v_{p}}{n} \right) \right] \]  
(A12)

\[ \frac{dP_{p_{m}}(z, v_{p})}{dz} = -\gamma_{p_{m}}(z, v_{p})P_{p_{m}}(z, v_{p}) \]  
(A13)

\[ \gamma_{s}(z, v_{s}, i) = \frac{A_{0}}{A_{0}} \left[ \sigma_{e}(v_{s}, i)N_{u}(z) - \sigma_{a}(v_{s}, i)N_{ab}(z) \right] \]  
(A14)

\[ \gamma_{cs}(z, v_{s}, i) = \frac{A_{0}}{A_{0}} \left[ \sigma_{e}(v_{s}, i)N_{u}(z) + \sigma_{a}(v_{s}, i)N_{ab}(z) \right] \]  
(A15)

For 980 nm pumping,

\[ \gamma_{p_{m}}(z, v_{p}) = \frac{A_{0}}{A_{p_{m}}} \left[ \sigma_{p_{u}}(v_{p})N_{i}(z) - \sigma_{p_{a}}(v_{p})N_{p}(z) + \sigma_{p_{a}}(v_{p})N_{ab}(z) \right] \]  
(A16a)

For 1480 nm pumping,

\[ \gamma_{p_{m}}(z, v_{p}) = \frac{A_{0}}{A_{p_{m}}} \left[ \sigma_{p_{u}}(v_{p})N_{i}(z) - \sigma_{p_{a}}(v_{p})N_{p}(z) + \sigma_{p_{a}}(v_{p})N_{ab}(z) \right] \]  
(A16b)

The spontaneous emission at 1.55 \( \mu \)m is taken as one photon per mode (for two polarization modes) per unit bandwidth.

In (A14) and (A16), clustered/paired ions are included as absorbers of both pump photons and signal photons. The occupations of the various states are given for 980 nm pumping by

\[ N_{i}(z) = \frac{K_{1}(z)}{K_{2}(z)} \]  
(A17)

\[ N_{p}(z) = \frac{K_{1}(z)}{K_{2}(z)} \]  
(A18)

\[ N_{u}(z) = N_{d} - N_{i}(z) - N_{p}(z) \]  
(A19)

with

\[ K_{1}(z) = \left[ 1 + \sum_{i=1}^{n} \frac{P_{s}(z, v_{s}, i)}{I_{s_{\text{sat}}}(v_{s}, i)i_{s}} \right] \left[ 1 + \left( \frac{P_{p_{0}}(z)}{I_{p_{\text{sat}}}(v_{p})A_{p_{0}}} + \frac{P_{p_{1}}(z)}{I_{p_{\text{sat}}}(v_{p})A_{p_{1}}} \right) \right] ^{2} \]  
(A20)

\[ K_{2}(z) = \left[ 1 + \sum_{i=1}^{n} \frac{P_{s}(z, v_{s}, i)}{I_{s_{\text{sat}}}(v_{s}, i)i_{s}} \right] \left[ 1 + \left( \frac{P_{p_{0}}(z)}{I_{p_{\text{sat}}}(v_{p})A_{p_{0}}} + \frac{P_{p_{1}}(z)}{I_{p_{\text{sat}}}(v_{p})A_{p_{1}}} \right) \right] ^{2} \]  
(A21)

\[ K_{3}(z) = \left[ 1 + \sum_{i=1}^{n} \frac{P_{s}(z, v_{s}, i)}{I_{s_{\text{sat}}}(v_{s}, i)i_{s}} \right] \left[ \frac{P_{p_{0}}(z)}{I_{p_{\text{sat}}}(v_{p})A_{p_{0}}} + \frac{P_{p_{1}}(z)}{I_{p_{\text{sat}}}(v_{p})A_{p_{1}}} \right] \]  
(A22)

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