Characteristics of a Yb-doped superfluorescent fiber source for use in optical coherence tomography

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Abstract: We have used a newly developed Yb-doped high-power fiber source in an optical coherence tomography (OCT) apparatus. We have analyzed various properties of interest for OCT measurements such as spectral shape, related gate width, central wavelength, bandwidth, and power output.

OCIS codes: (110.4500) Optical coherence tomography; (120.4290) Nondestructive testing; (060.2380) Fiber optics sources and detectors

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#5994 - $15.00 US Received August 21, 1998; Revised October 06, 1998

1. Introduction

Optical coherence tomography (OCT) is a recently developed gated optical imaging technique that shows promise in biomedical [1,2] and nondestructive evaluation [3,4] applications. Optical gating in OCT is based on low coherence interferometry, and represents an extension to two dimensions of a technique used to find defects in optical waveguides [5-7]. Due to its excellent gating properties, OCT can be used to image structures inside highly scattering media where other optical imaging techniques fail because of the presence of scattered light. Because the optical gate, related to the optical field correlation function, is determined by a Fourier transform of the optical spectrum, the spectral shape of the optical source, is perhaps the most important and critical component in any OCT system. Commercial super-luminescent diodes at 850 nm produce near-Gaussian spectral shapes with reasonably small modulation in the correlation signal and are common light sources for OCT devices. In biological applications, where the total incident light power is limited due to ANSI standards, the one to two mW output from these devices is sufficient. However, in many applications of OCT, such as detecting defects in materials, no such strict power limitations are present. In those cases higher power light sources could be used for a better signal-to-noise ratio or for deeper probe penetration. Also, higher power can be beneficial for non-scanning, two-dimensional optical gates [8]. Consequently, the need is there for broadband, high-power optical sources with near-Gaussian spectral shapes.

Superfluorescent fiber sources are known at various wavelengths. A broadband amplification gain of almost 10 dB centered at 1.3 µm was demonstrated from a Pr^{3+}-doped fluoride fiber amplifier [9]. A recently developed broadband light source (Galileo) produces about 5 mW of amplified spontaneous emission (ASE) in a near-Gaussian spectral profile. This source, however, is new, requires a pump wavelength which is not standard, and is relatively expensive to fabricate. In contrast, Er-doped fiber amplifiers are commonplace in the fiber industry and are relatively inexpensive. However, they commonly have spectral structure and their bandwidth is relatively narrow. Some work has been done recently to shape the spectrum of these sources using long period fiber Bragg gratings [10], but this is an added complication and expense. Another, potentially useful source at 1.81 µm, was recently used in OCT measurements [11]. This source was based on a Tm-doped silica fiber with a reported output power of 7 mW and bandwidth of 80 nm, corresponding to a longitudinal gate width of 18 µm .

In this work we measured and analyzed various parameters relevant to OCT of a newly developed superfluorescent fiber source at ~1.064 µm [12]. In particular, we measured the total optical output power, bandwidth, and central wavelength as a function of pump laser power. We also used this source in an OCT apparatus for the direct measurement of the correlation function from a mirror surface.

2. Source

The general construction of our ASE source is similar to that described in Ref. 12. Here we used a 10 m long (Lucent Technology) fiber with a polymer outer cladding, a 131 µm wide (on the diagonal) near-hexagonal inner cladding with a numerical aperture (NA) of 0.45, and an Yb-doped single mode core with a diameter of 6 µm and a NA of 0.15. The absorption coefficient was 2.2 dB/m for 975 nm pump light propagating in the inner cladding. The emission of a 200 µm wide broad stripe laser diode (Siemens), emitting at 975 nm, was coupled into the fiber inner cladding using the v-groove side-coupling technique [12], resulting in a diode-to-fiber coupling efficiency of approximately 65%. Double cladding fiber ends were pigtailed by fusion splicing to lengths of conventional single mode fibers (Corning Flexcore 1060). All of the components of the fiber amplifier ASE source, except for the current source, were packaged in a 10x12x1.5 cm metal housing.

At the maximum diode power of 2.1 W, generated at a current of 2.5 A, the ASE source emitted 700 mW in the direction counter-propagating to the pump light, and 320 mW in the direction co-propagating to the pump light. For the counter-propagating direction, at the maximum pump power, the emission spectrum was observed to have a flat-top profile that extended from approximately 1040 nm to 1080 nm [12].

3. Measurements

The output power, spectral shape, and spectral position of our source depend on various parameters. In general, the output ASE power in the direction counter-propagating to the pump is approximately two times higher than in the co-propagating direction. However, the spectral shape is more Gaussian-like in the co-propagating direction. For this reason, we chose to analyze the co-propagating ASE in this work. Figure 1 shows the power dependence of the total, unpolarized ASE on the pump laser power.

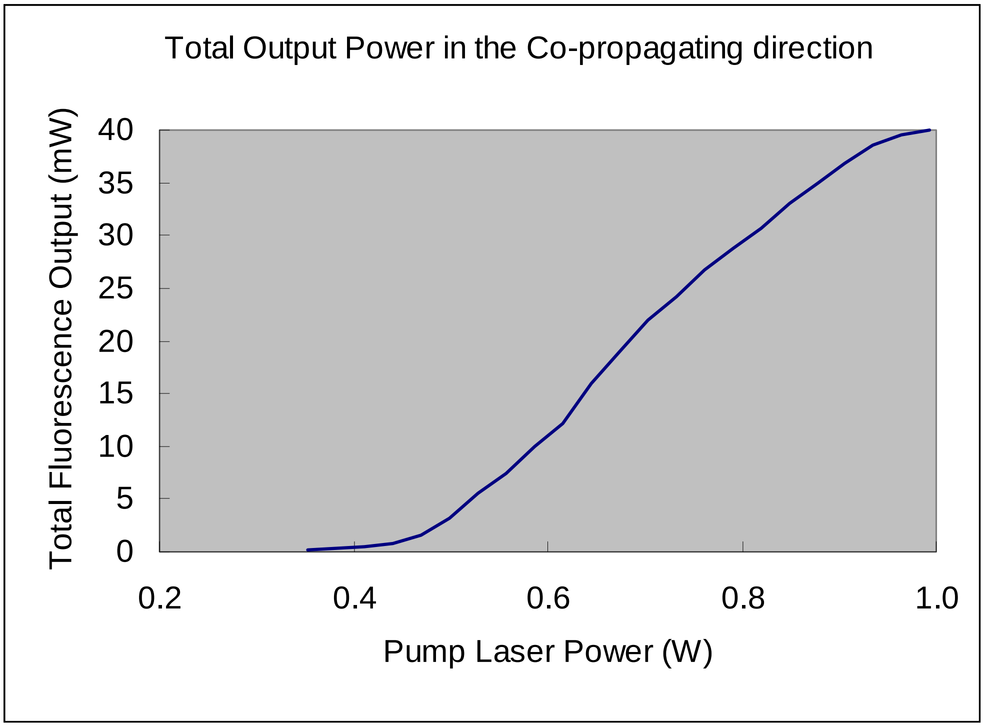

Fig. 1. The total ASE output power from a Yb-doped fiber source as a function of the fiber-coupled pump laser power. The ASE power was measured in the direction co-propagating with the pump, directly at the fiber output.

As seen in Fig. 1, the maximum output power in the co-propagating direction is approximately 40 mW at a fiber-coupled pump power of 1 W. The output power depends critically on back-reflections into the fiber. Even small reflections can cause significant power reduction or lasing to occur. We believe that some back-reflection was present for the measurements shown in Fig. 1 since other measurements in a slightly different configuration produced up to 60 mW of ASE output at a pump laser power of 0.76 W. We also observed lasing for pump powers exceeding 1 W in the experimental setup reported in this work. It is

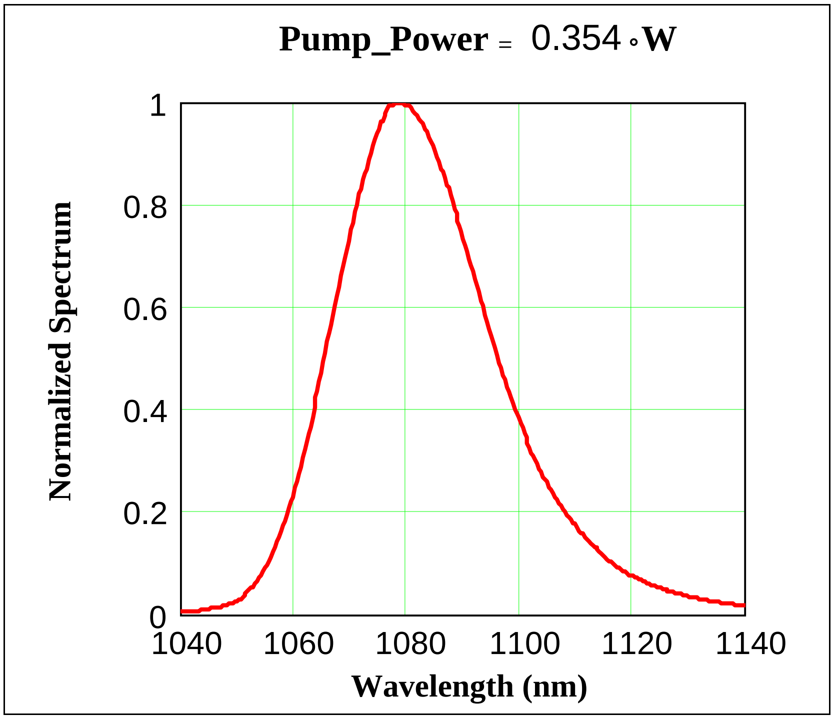

Fig. 2. A movie showing the co-propagating ASE spectrum as a function of the pump laser power.

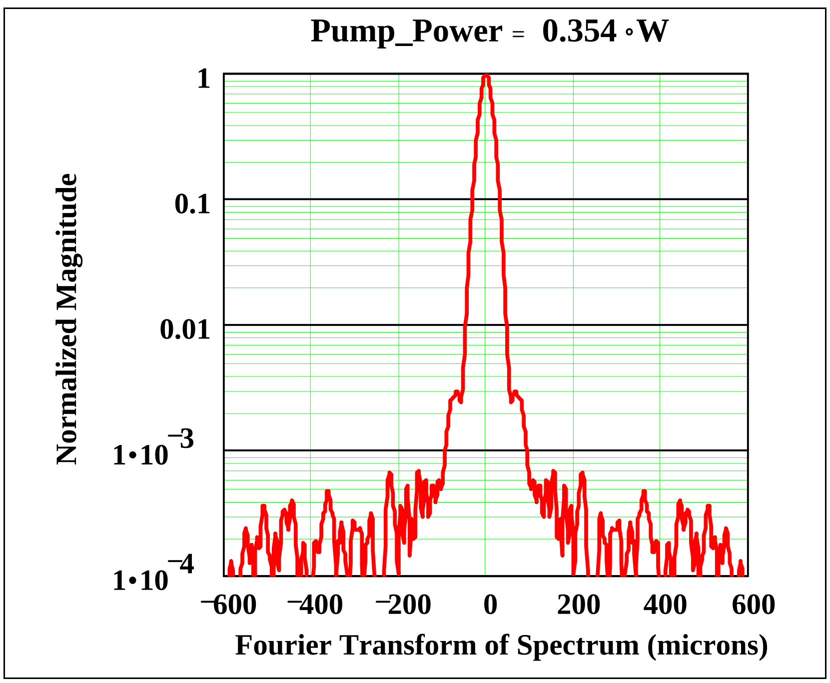

Fig. 3. A movie showing the calculated Fourier transform of the ASE output power spectrum as a function of the pump laser power.

likely that for OCT measurements an optical Faraday isolator will be required to prevent back-reflections into the amplifier. This requires the ASE output light to be polarized and could cause a reduction in the total output power. Even with these losses, output powers of a few tens of mW should be easy to achieve.

The spectrum of the ASE light coming from the co-propagating end of the fiber is shown in the movie of Fig. 2 as a function of the pump laser power. The broadest bandwidth, 31 nm, occurs at a pump power of 0.35 W and decreases to 24 nm at a pump power of 0.76 W. The peak wavelength also shifts from 1.08 μm to 1.07 μm as the pump laser power increases from 0.35 W to 0.76 W. Visually, the spectral shape appears smooth and unmodulated at all power levels. This is important for the OCT correlation function and indicates that the depth resolution of the OCT device will not be degraded significantly. To validate this, we Fourier transformed the measured output power spectral shapes. The resulting curves, shown in the movie of Fig. 3, indicate that the worst side-lobes produced by the deviations from the Gaussian spectral shape are only 4% of the central peak at the highest pump power. As expected, the worst side-lobes are produced at the highest pump laser power.

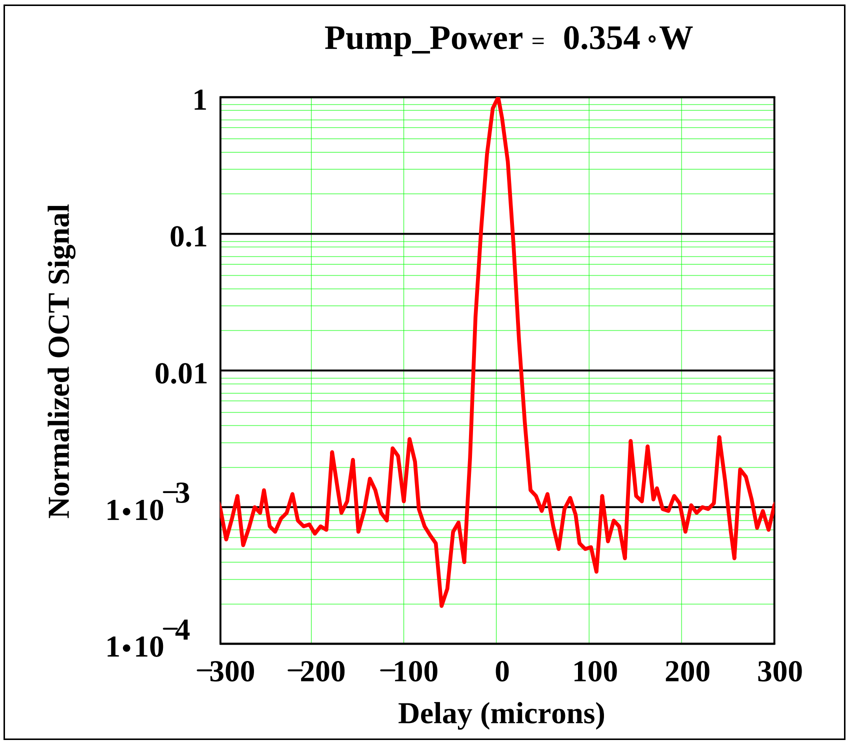

Fig. 4. A movie of the measured OCT signal as a function of the pump laser power.

We also performed direct OCT measurements to verify the shape of the correlation function. Direct measurements of the correlation function are important since other experimental factors can cause distortion of the spectrum. For example, the InGaAs detectors used for this wavelength range have a wavelength-dependent response. This is equivalent to spectral modulation being present in the light. The movie in Fig. 4 shows the OCT signal from a reflecting surface taken at various pump laser powers. The shape of the measured OCT signal is very similar to the calculated correlation function. One difference, surprisingly, is that the side-lobes, due to all sources of spectral modulation, are below the noise level at the lowest pump power and only reach 1% of the central peak at the highest pump power. The measured full width at half maximum is approximately 20 μm at a pump laser power of 0.35 W and increases to approximately 30 μm at a pump laser power of 0.76 W.

4. Summary

We have characterized a new, high-power broadband source, based on Yb-doped fiber, for use in OCT. High power and good spectral properties make this source an excellent candidate for any OCT apparatus and in particular for non-destructive testing and evaluation of ceramic and other materials, where higher powers can be used. We plan to characterize this source further under various conditions of back-reflections from one end of the fiber. We will also investigate spectral shaping for increasing the total ASE bandwidth. Finally, we will use this source in an OCT apparatus for the nondestructive inspection of ceramics and other materials.

Acknowledgments

We would like to acknowledge the support of the Office of Naval Research.