Optical fiber sources for measurement and imaging

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ABSTRACT

An overview of the different type of fiber broadband sources and some fiber laser sources that operate as incoherent sources, are briefly discussed and some practical applications are presented. The optical performance and characteristics of several of these fiber sources are reviewed, including emission spectra profiles, autocorrelation functions, wavelength and power stabilities, and polarization behavior.

Keywords: Narrowband fiber sources, broadband fiber sources, tunable fiber sources, swept fiber lasers, optical coherence tomography, optical imaging, fiber Bragg grating sensors.

1. INTRODUCTION

Fiber optic sources based on rare-earth doped-glass fibers have been emerged as promising optical sources in some industries, particularly for navigational-grade fiber optic gyroscopes (FOG) applications, wavelength-division-multiplexing (WDM) sensing networks, on industrial inspection low-coherence interferometry (LCI), and on some biomedical applications, such as optical coherence tomography (OCT). In most of these applications, the optical source must be spectrally broad in order to minimize errors due to coherent effects. Furthermore, they should offer high output power (>10 mW) in a single-mode fiber to improve the signal-to-noise ratio, and in some special cases, a single-polarization maintaining output with high polarization extinction ratio (PER>22 dB) is needed. Additionally, some measurement applications require a central wavelength and spectral density output power that are very stable with environmental temperature fluctuations. With these optical requirements and some mechanical constrains, such as, dimensions and vibrations-free capability, the manufacturing process of commercial and reliable optical fiber sources is a great challenge but feasible. Advances of the optical components fabrication and on the careful fiber design configurations, have allowed the manufacture of fiber optic sources which maintain their performance parameters over time even when subject to temperature and vibration perturbations found in real applications. We report some of these advances on our developed optical fiber sources and show some results on different types of measurement and imaging applications.

2. BROADBAND FIBER SOURCES FOR IMAGING

Rare-earth superfluorescent fiber sources (SFS) provide high output power, broadband and fiber coupled signal required for many optical components testing procedures and biomedical imaging. The round trip gain of a typical SFS ranges from 40 to 60 dB and thus even minor reflections occurring simultaneously at the ends will turn the SFS into a laser. Owing to the relative ease of its design and lower propensity for lasing, single-pass backward configuration has been widely used for rare earth SFSs. A double pass configuration either forward, or backward, allows for a higher gain but also requires more caution in order to preclude the SFS from lasing. In fact lasing can occur not only from point reflections at components or fiber terminations but also from Raleigh backscattering. Unwanted lasing in ASE based super fluorescence sources occur when roundtrip phase and polarization line up and the round trip gain reach unity. Lasing threshold in ASE based broadband sources can be pushed to higher pump powers and thereby increased super fluorescence signal power by reducing back reflections and decreasing peak gain through seeding with signal outside the peak thus saturating the gain. One lasing suppression technique relies on destruction of round trip polarization consistency by using a Faraday rotator mirror (FRM) [1], which gives a non-reciprocal rotation of the state of polarization and may be used for this purpose. Also typically the output spectrum of SFS sources has spectral structure,

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which leads to undesired effects in the coherence function of the source, such as side lobes, limiting its application for example, in medical imaging. The most common way to achieve emission with broader smoother spectrum is spectral filtering. If applied to the output of the SFS source this technique also results in a significant decrease of optical power. However if filtering is applied to a low-power seed re-injected to the gain fiber, then power efficiency can be maintained. In such configuration either forward or backward ASE can be filtered and seeded back for amplification within the SFS[2]. The filtering element can be a bulk grating [2], a set of fiber Bragg gratings [3] (FBG) or a length of unpumped rare-earth doped fiber [4].

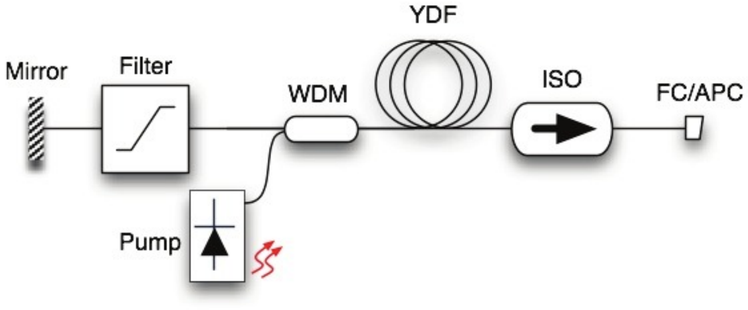

Fig. 1. SFS source with filtered backward ASE seeding [1].

Figure 1 illustrates a SFS source with filtered seeding of backward ASE. A 5 m long ytterbium-doped fiber (YDF) is pumped at 980 nm through a fused WDM. At a pump power of 150 mW the forward superfluorescence spectrum is varied as a function of back reflection set by the mirror. Figure 2 shows the effect of the filtered ASE seeing on the forward output spectrum [1]. As shown, significant spectral reshaping can be achieved with this technique while keeping high power efficiency. Also an increase in the lasing threshold was observed. Such effect results from the gain saturation induced by the seeded signal. The figure 3 shows the correspondent autocorrelation function of the filtered ASE spectra measured as a function of the optical path difference (OPD) of a Michelson interferometric setup.

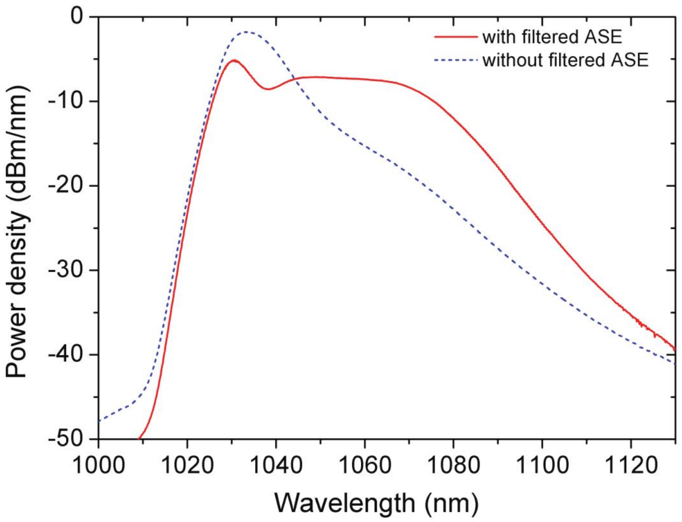

Fig. 2. SFS emission spectra with (solid) and, without (dash) filtered backward ASE.

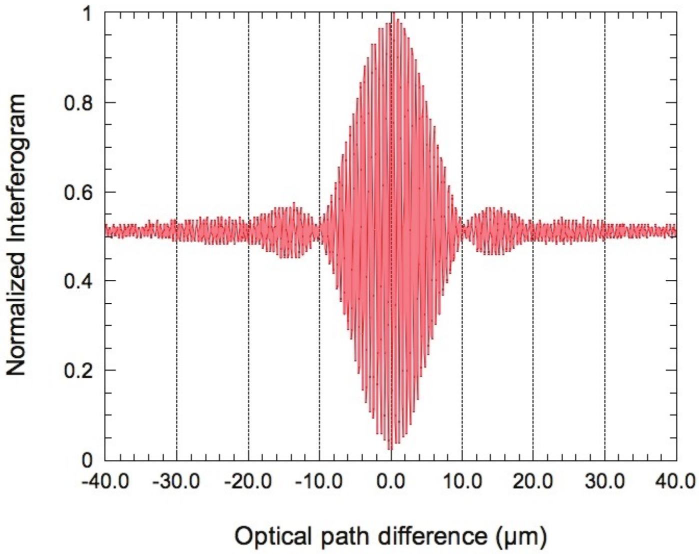

Fig. 3. Measured autocorrelation function of the SFS emission with filtered backward ASE technique.

3. NARROWBAND FIBER SOURCES FOR FIBER OPTIC SENSORS

In some fiber optic sensing applications, particularly, the ones that use fiber Bragg grating (FBG) devices as sensor elements, a temperature stability and high power spectral density source (>10 dBm/nm) with a flat-shape spectra emission, are required. With these optical source characteristics one can ensure a good and uniform SNR to all sensors and have a higher remote measuring distance, which in some cases, is a crucial factor due to safety regulations. A proprietary narrowband high power ASE fiber source was fabricated having these criteria in mind, and was recently demonstrated [5] on a multi-point fiber optic temperature sensor network integrated inside a power transformer for continuous monitoring of hot-spots on windings, cellulose insulations and oil. Figure 4 shows the narrowband and spectrally flat ASE fiber optic source (N-ASE), emitting at central wavelength of 1550 nm with ~55 mW output optical power and ~7 nm spectral width (FWHM). It was used to illuminate the FBG sensing network deployed inside the power transformer. Figure 5 shows schematically the tested configuration of the multi-point fiber optic sensor (MPOS) unit.

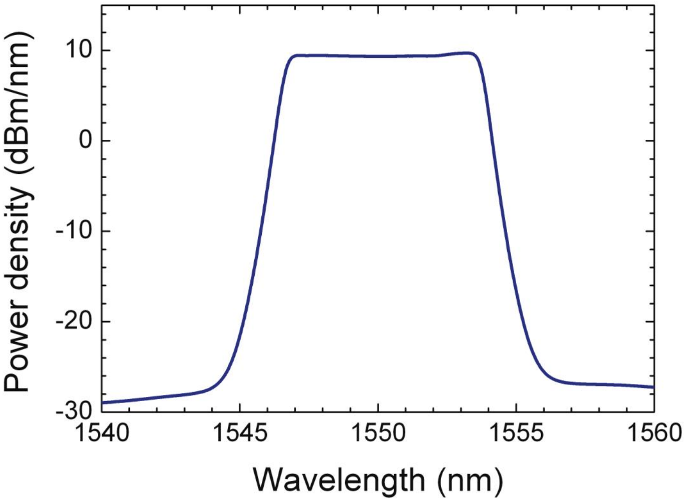

Fig. 4. Emission spectra of the narrowband ASE fiber source.

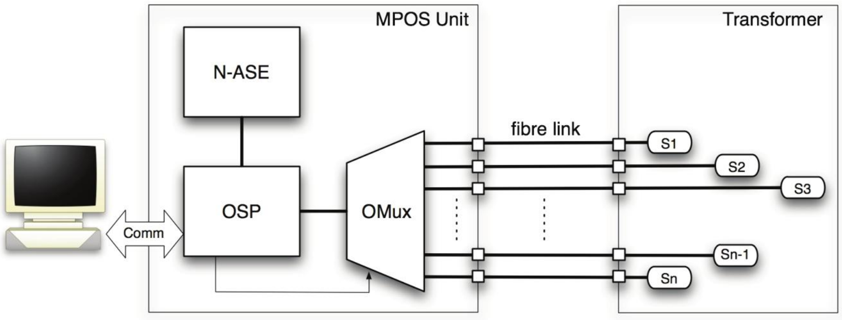

Fig. 5. Schematic diagram of the multi-point fiber optic sensor unit. (N-ASE: narrowband ASE fiber optic source, OSP: optical signal processing module, OMux: addressable optical multiplexer, Sn: FBG sensor number n. [5].

4. TUNABLE NARROWBAND FIBER SOURCES FOR SEMICONDUCTOR PROBING

Internal probing of CMOS circuits is a critical capability for efficiently ramping from prototypes to volume production of advanced integrated circuits. The first commercially available optical backside probing tool was introduced in 1999, known as the Laser Voltage Probe (LVP), and used a non-contact, through-silicon technique for measuring the electrical activity inside an integrated circuit [6]. Very recently, a new improved measurement technique similar to LVP was demonstrated using a new acquisition scheme based on polarization-dependent optoeletronic effects in silicon [7].

This technique designated a Polarization Difference Probing (PDP), provides a better noise immunity and improved signal sensitivity, with a noise floor twice lower than the best LVP system. In these standard-probing systems, the electrical activity of an IC is predominantly encoded in the phase of the 1064 nm laser beam reflected from the active regions of the IC. To detect this phase information, a Michelson interferometer is used, and the LVP phase signal is extracted with the help of sophisticated noise reduction techniques that includes active feedback control of the interferometer reference arm path length. On the other hand, the PDP technique uses a dual-laser noise reduction scheme, where paired measurements are made during each repetition of the device under test (DUT) signal, using a sampling optical pulses from two lasers [7], one a 10-ps mode-locked laser (MLL) and the other a CW tunable narrowband low coherence fiber source (TNBS) with 15-ns rise time amplitude modulation capability which has been specially designed by Multiwave.

The effectiveness of the dual-laser scheme depends crucially on how well the MLL and the TNBS are spectrally matched with their interactions with both the DUT and the system optics, being the important parameters central wavelength, spectral width and power density. Figure 6 shows the emission spectra of both sources, the MML (dash curve) and TNBS (solid curve). The developed TBNS source emitted an optical output power of 5 mW, at a central wavelength of 1064.4 nm, spectral width 0.35 nm (FWHM) with an output PER higher than 21 dB. Crucial to this application is the spectral and optical power stability of the source over temperature variations in time. The emitted output power and central wavelength variations with a temperature varying between 10ºC and 40ºC during a 4-hour period cycling test were 0.07 dB and <0.01 nm (limited by the OSA resolution), respectively. Figure 7 shows a temperature cycling test of one of the cited parameters. The wavelength tunability range of this source was ±0.4 nm from the central wavelength.

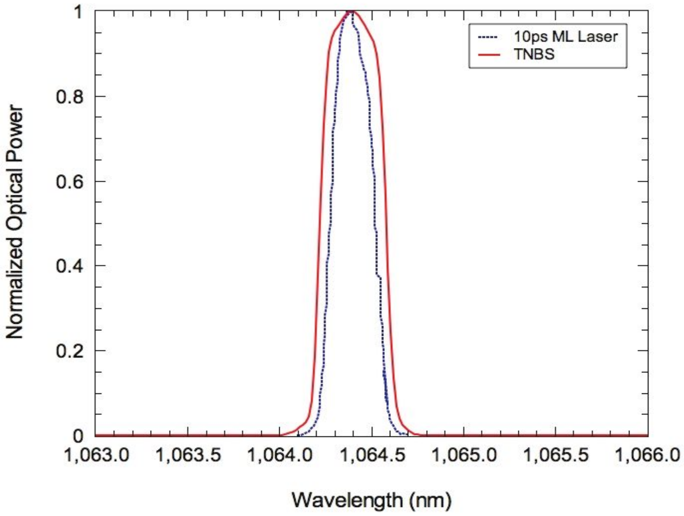

Fig. 6. Emission spectra (linear scale) of the 10-ps MLL (dash) and TNBS fiber source (solid).

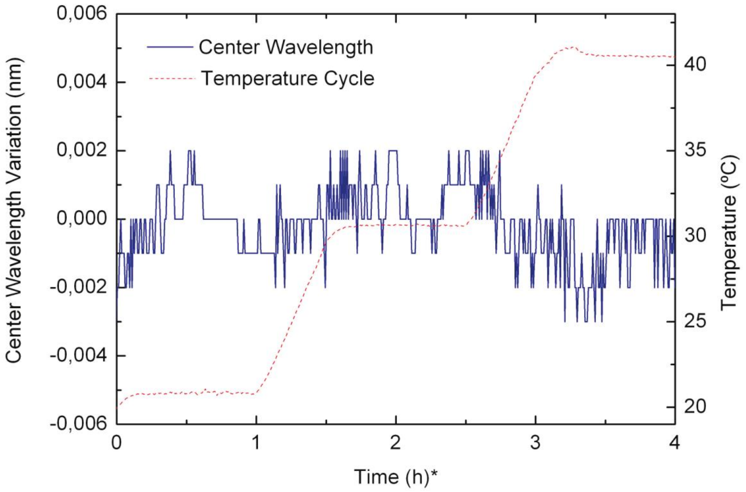

Fig. 7. Central wavelength stability of the TNBS fiber source during a temperature cycling test. The total variation is 0.005 nm over 4 hour period.

5. SWEPT FIBER SOURCE FOR LOW COHERENCE INTERFEROMETRY

Fast tunable optical sources, also designated as swept optical sources, have attracted larger interest on the imaging fields, in particular on Medicine, where the Optical Coherence Tomography (OCT) has been winning the acceptance of the ophthalmology community. Although, the OCT systems operating at a 820 nm wavelength band are relatively well established as a commercial products. These operate with CW semiconductor sources, such as superluminescence diodes (SLD) with relatively low power and their OCT optical signal processing is more complex. Since the scattering losses in the retina becomes more significant at wavelengths in the visible region, and the absorption and dispersion of the vitreous humor is high at 1550 nm, other wavelengths for OCT are being now considered. In particular, the spectral window between 1000-1100 nm offers a low absorption and dispersion in water and allows deeper penetration at the retina [8,9]. Adding to this, the OCT techniques that use a swept source instead of a CW broadband source, offers enhanced signal-to-noise ratio, high imaging speed, the availability of ultrahigh resolution imaging as the broadband sources and simpler detection by the use of a single-point photodiode. Ytterbium-doped fibers can provide broadband gain through the 1050 nm region, and with some careful cavity design topologies it's feasible to fabricate a compact swept all-fiber source with no moving parts. Figure 8 shows preliminary experimental results of a prototyped optical source of this kind, emitting a total output power of +10 dBm, with a SNR ~50 dB, a spectral linewidth of ~0.16 nm (FWHM) with a total scanning wavelength range of about ~50 nm and a maximum swept frequency of ~50 kHz. The long term reliability and optical performance still needs to be tested in order to become a viable commercial product. Another important physical parameter is the form factor of the source, which needs to be compact for a seamless integration into the OCT system. For this prototype the physical dimensions were 160 mm x 110 mm x 23 mm.

In some other OCT applications, like optical imaging of hard and soft dental tissue, C-band (1529 to 1568 nm) and L-band (1560 to 1600 nm) wavelengths have been used [10]. Figure 9 shows the peak-hold spectrum obtained by a second prototype swept source, build with an erbium-doped fiber in a different optical cavity configuration from the previous one, and emitting in the L-band region with an optical output power of 5 mW (being the maximum output power for this source, 10 mW), and a spectral linewidth narrower than 0.05 nm. The wavelength swept range shown in the figure 9 (~15 nm) was limited only by the electronic driving circuit used, being the maximum wavelength tuning range ~40 nm.

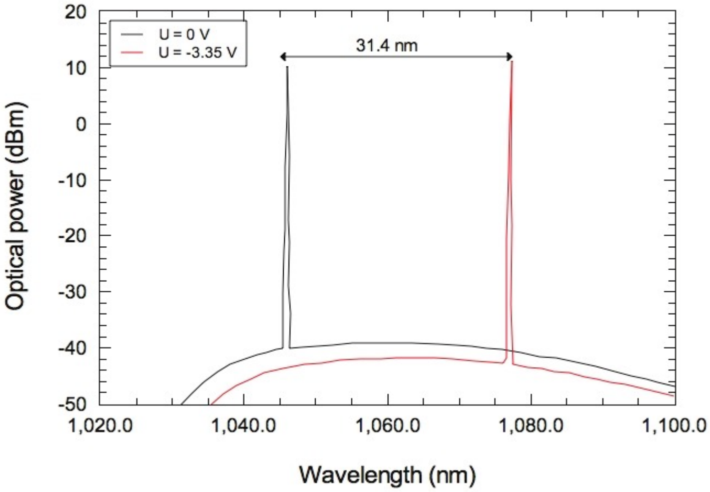

Fig. 8. Emission spectra of the prototype Yb-doped swept fiber source at two wavelength-setting points.

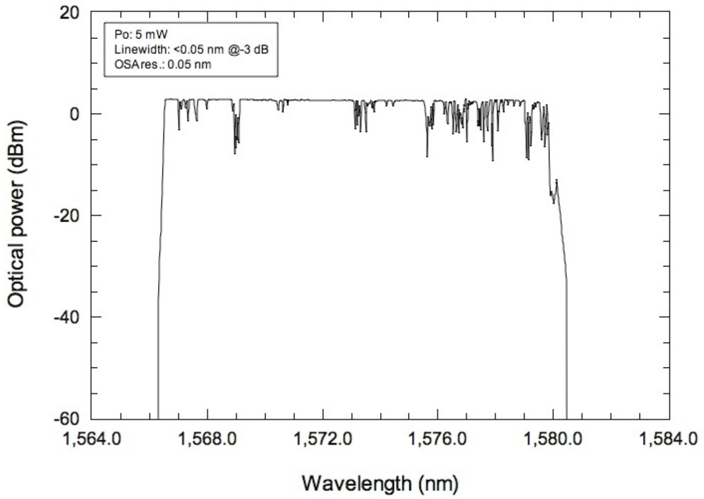

Fig. 8. Peak-hold mode output spectrum of the L-band prototype swept fiber source (scanning speed: 1 ms).

6. CONCLUSIONS

We have reviewed some of the optical fiber sources that Multiwave has developed and tested on different measurement and imaging applications. Optical sources for imaging systems are available in several technologies, grouped into “broadband” or “scanned wavelength” sources. Broadband sources are the most commonly used, however wavelength scanned sources are of interest as they allow simpler and cheaper detector geometries, particularly for wavelengths greater than 1 µm, where detector cost is very significant. From the results discussed here, it can bee seen that the optical sources based on all-fiber technology are a good candidate for measurement and imaging applications. Being all fiber technology, one can foresee a higher integration of part of the OCT imaging system which will be made in part of special fiber components, resulting in a more compact, stable and vibration free unit giving to the manufacturer a easier and faster product integration. Due to the low coherence characteristic and the high optical power spectral density of the narrowband fiber sources demonstrated, make them a good optical source solution for large FBG sensing networks and for high resolution industrial optical testing.

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