Optical Sensor Based on Depressed Cladding Erbium Doped Fiber Ring Laser for Ultrasonic Sensing

**Mauro Biscaro Elias\*, João Batista Rosolem\*\* and Carlos Kenichi Suzuki\***

\* Faculty of Mechanical Engineering, State University of Campinas, Campinas, SP, 13083-970, Brazil

\*\* CPqD – Research and Development Center in Telecommunications, Campinas, SP, 13086-902, Brazil

**ABSTRACT**

*Depressed-cladding (often referred to as dual-clad or “W”- fiber) fibers with fundamental-mode cutoffs provide high distributed losses at long wavelengths and low losses at short wavelengths. The magnitude of the abrupt transition between low-loss at short wavelengths and high-loss at long wavelengths exceeds and is found to be extremely sensitive to fiber curvature. The phenomenon is attributed to mode coupling between the core-guided mode and the discrete modes guided in the outer cladding. The active depressed-cladding fiber () may be designed to have a fundamental mode cutoff near and provides distributed suppression of C-band amplified spontaneous emission () to the advantage of that in the S-band. This phenomenon, associated with the mechanism of induced bending loss, provides an alternative approach to obtain amplification in S-band, required to expand the capacity of wavelength-division multiplexing (WDM) systems. S-band depressed-cladding erbium-doped fiber ring laser which can be tuned through the active fiber bending losses or by using an optical tunable filter, can thus be designed. Due to the amplification and lasing characteristics developed for S-band, based on unique properties, the was the basis of the optical sensing system developed in this work. In fact, the sensing system proposed showed high sensitivity, high dynamic range and wide bandwidth, and can be used to monitor static parameters, such as force, pressure, displacement and dynamic parameters used in acoustics and vibrations. The performance of this sensing system in S-band () was studied and analyzed in static and dynamic conditions. As this ring laser optical sensing system detects ultrasonic sound waves it can be used in virtual reality tracking systems and augmented reality.*

**1. INTRODUCTION**

Depressed-cladding fibers, or “W”- fibers, are double cladding light guide structures with inner cladding having lower refractive index than outer cladding. When those fibers have their core doped with Er ions () they become an active fiber and are referred in literature as active W-fiber, or depressed-cladding erbium doped fiber (DC-EDF). Depressed erbium doped fiber was developed a few years ago for optical amplification in the S-Band (1480 - 1525 nm) in Dense Wavelength Division Multiplexing (DWDM) system channel expansions. It has been pointed out that the behavior of DC-EDF is very sensitive to the bending radius, which is used to suppress the C-Band amplified spontaneous emission (ASE) generated by erbium doped fiber, thus enabling S-Band optical amplification.

Moreover, DC-EDF has been studied for ring laser. The wavelength tuning range mainly depends on the gain bandwidth of the active medium and the tuning range of the filter. Both of the Raman and Er3+-doped fiber amplifiers (EDFAs) can provide a very wide gain bandwidth of up to 100 nm and, for EDFAs, the laser amplification can occur either at S- (1480 ~ 1520 nm), C- (1530 ~ 1565 nm) or L- (1570 ~ 1610 nm) bands contingent upon the erbium ion concentration, length of the erbium-doped fiber (EDF) and/or amplified spontaneous emission (ASE) suppressing filter. Tunable Er3+-doped fiber lasers had been demonstrated using tunable filters. Among them, the fundamental mode cutoff wavelength (LP01-λc) induced from a depressed inner cladding is distinguished for wideband distributed ASE suppression and was employed to achieve tunable S-band EDFAs and fiber lasers [Arbore, 2005; Arbore et. al., 2003]. The ASE peak wavelength and the longer wavelengths are substantially suppressed while the short wavelengths in S-band can thus obtain higher population inversions and sufficient amplification. The cutoff wavelength can be tuned by bending the fiber and the total distributed loss for wavelengths longer than the cutoff is > 200 dB through entire length of the EDF [Arbore et. al., 2003].

This paper describes a new type of acoustic sensing system based on DC-EDF ring laser. We described a DC-EDF acoustic sensing system and its characterization in S band (1495 to 1515) nm in a frequency range from 5 Hz to 60 kHz. Our purpose is to explore the bending/lasing mechanism of DC-EDF in order to obtain a highly sensitive sensing system which can be used in many areas of interest, such as, electric energy, civil engineering, virtual reality tracking systems and augmented reality [Azuma et. al., 2001]

# 2. EXPERIMENTAL SET-UP

The principle of operation of the proposed optical fiber sensing system is based on the DC-EDF, which can also be referred to as dual-clad or W-profile erbium doped fiber. It has been demonstrated that the ASE of erbium-doped fibers can be suppressed in the C-band, to take advantage of the S-band amplification, due to the fundamental mode cutoff (LP01-λc) of DC-EDF. The design of a DC-EDF has the cutoff wavelength at about 1525 nm, distributed loss > 200 dB for C-Band, and distributed loss in the S-Band much less than the gain. Distributed fiber loss or the distributed fiber gain at S-Band depends on fiber bending to suppress the C-Band ASE in a certain bending radius which is generally smaller than 50 mm.



*Fig. 1. Basic configuration of the DC-EDF laser-ring sensing system experimental* *set-up*.

The basic configuration of the laser-ring sensing system is depicted in Figure 1. An optical splitter (90/10%) was used at the sensing system output to obtain a sample of laser light (10% port) and to connect the counter-propagating ASE power generated by the near end DC-EDF (90% port) in to the far end of DC-EDF. The laser stability and tuning were achieved by using one isolator and one tunable optical filter in the feedback loop, respectively. The DC-EDF was pumped by a co-propagating pump scheme using one 980 nm laser. In the sensing system output (10 % port) we utilized an optical spectrum analyzer (OSA) or an optical receiver Rx (photo-detector (PD) plus trans-impedance amplifier (TIA)), followed by one audio amplifier and an oscilloscope. The DC-EDF used comprises an Er–La–Al-doped core, and the 980 nm pump absorption is 7.6 dB/m. The C-band bending loss exceeds 10 dB/m for a 30 mm coil radius. Based in previous amplification experiments we have chosen the DC-EDF length of 12 m coiled in a 50 mm radius [Rosolem et. Al., 2005]. The 980 nm pumping power in the DC-EDF fiber input was 50 mW. Figure 2 shows the S-band ring laser output power. Figure 3 shows some ring laser spectral lines. Due to limitation of tuning range of the optical filter, the laser-ring could not operate in wavelengths lower than 1495 nm; operation above 1517 nm was not possible as well due to the cut of the fundamental mode of the DC-EDF.

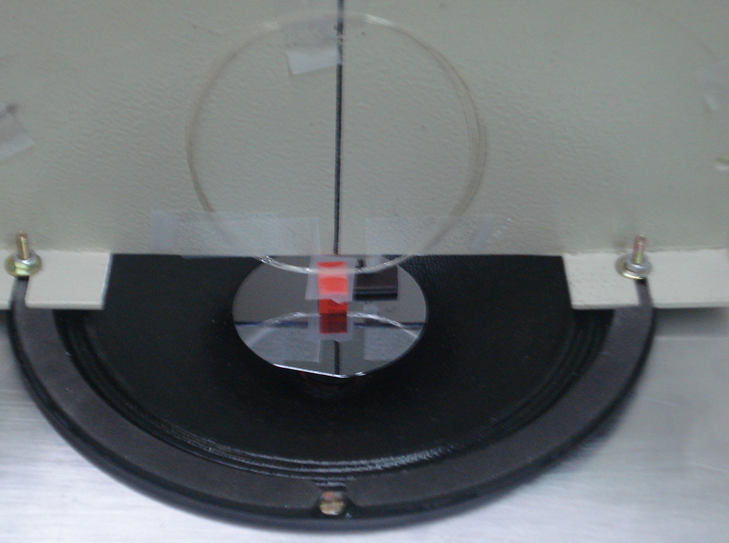


*Fig. 2. Output power of the ring laser*



*Fig. 3. Spectral lines of the ring laser.*

The characterization of the sensing system was done using one acoustic transducer, which excited mechanically the optical fiber ring laser (Figure 4). The electrical signal connected to the acoustic transducer was supplied by a signal generator and amplified by an electrical amplifier. A calibrated Hall sensor was coupled to the acoustic transducer followed by one amplifier and the oscilloscope in order to measure the mechanical displacement of the optical fiber ring laser radius caused by the acoustic transducer.



*Fig. 4. Details of the setup of the optical fiber ring laser loops in the acoustic transducer.*

**3. RESULTS**

In order to perform the acoustic characterization, the loops of the ring laser were oriented in a vertical position (Figure 4) and were fixed in two points. The DC-EDF ring-laser sensor was first excited mechanically in 100 Hz by the acoustic transducer in different radius variations (ΔR) ranging from 17 to 727 µm in order to search for the sensor linearity. Figure 5 shows the linear behavior of the peak-to-peak voltage measured by the optical receiver Rx for four different tuned wavelengths versus the DC-EDF ring laser radius variation. As we can observe in Figure 5 the linearity of the sensing system is very good mainly for wavelengths of 1495 and 1505 nm.



*Fig. 5. Peak-to-peak voltage measured by the optical receiver Rx for four different tuned frequencies versus the DC-EDF radius variation.*

Next, the DC-EDF optical fiber ring laser sensor was mechanically excited from 5 Hz to 50 kHz by the acoustic transducer for one fixed value of loop radius variation ΔR = 4 µm. We used this radius variation in order to get the highest frequency as possible reproduced by the acoustic transducer. Figure 6 shows the spectral performance of the laser ring sensing system for the wavelengths of 1495 and 1510 nm. The spectral behavior is certainly no flat, but the sensitivity is very good from low to high frequencies.



*Fig. 6. Spectral performance of the DC-EDF laser ring sensing system from 5 Hz to 50 kHz for ΔR = 4 µm.*

Figure 6 shows the formation of resonance peaks in the sensor signal. This behavior can be understood using a simplified model of string resonance. The sensor resonance has dependence with some fiber loop parameters, such as applied strain, length, radius, points of fixing (acoustic nodes) and fiber material constants [Zervas, Giles, 1988]. When the fiber loop is tensioned by the acoustic transducer, the transverse waves propagate to the fixing end point, where they are reflected undergoing constructive interference and leading to the resonance frequencies. Figures 7(a) to (e) show examples of waveforms collected by the oscilloscope for DC-EDF sensor from 5 Hz to 50 kHz, 1495 nm, ΔR = 4 µm and Figure 7(f) shows an example of waveform colleted by Hall sensor for 5 kHz. As we can observe the waveforms are undistorted except for 50 kHz, because of the filtering employed to minimize the ASE noise which is created in the lasing process. Because of the limitations of the acoustic transducer, the measurements could not extend above 60 kHz. Since the sensing system can detect ultrasonic frequencies (>20 kHz) it is possible to use it in many interesting applications, such as partial discharge detection in power transformers, hydro-generators and in virtual reality tracking systems and augmented reality. In low frequencies, the sensing system can also be used to detect vibrations in large structures such as bridges and dams. Table 1 presents a summary of the performance of the DC-EDF laser ring sensor.



*Fig. 7. Time waveforms of the DC-EDF laser ring sensing system from (a) 5 Hz, (b) 50 Hz, (c) 500 Hz, (d) 5 kHz, (e) 50 kHz and (f) 5 kHz (Hall sensor) for 1495 nm and ΔR = 4 µm.*

Table 1 summarizes the performance of the DC-EDF laser ring system proposed.

TABLE 1

DC-EDF laser ring performance summary

|  |  |
| --- | --- |
| Parameter | DC-EDF laser-ring sensor |
| Minimum detectable vibration frequency (Hz) | 5 |
| Maximum detectable vibration frequency (Hz) | 60.000 |
| Sensitivity (mV/µm) | 6,4 |
| Minimum detectable radius variation (µm) | 4 |

**4. CONCLUSION**

This work described a new type of optical sensing system based on Depressed Cladding Erbium Doped Fiber (DC-EDF) ring laser. Due to the amplification and lasing characteristics developed for S-Band applications this DC-EDF ring laser sensing system has high sensitivity, high dynamic range and wide bandwidth. It can be used to monitor static parameters such as force, pressure, displacement and dynamic parameters such as in acoustics and vibrations.

We described the DC-EDF ring laser sensing system characterization in S-band (1490 to 1510 nm) in two different conditions: static and dynamic. The DC-EDF ring laser sensing system proposed showed good performance in frequencies from 5 Hz to ultrasonic sound waves frequencies of 60 kHz, and could be used in virtual reality tracking systems and augmented reality.

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