June 2017
Vol. 31, No. 3
www.PhotonicsSociety.org

IEEE photonics Society NEWS

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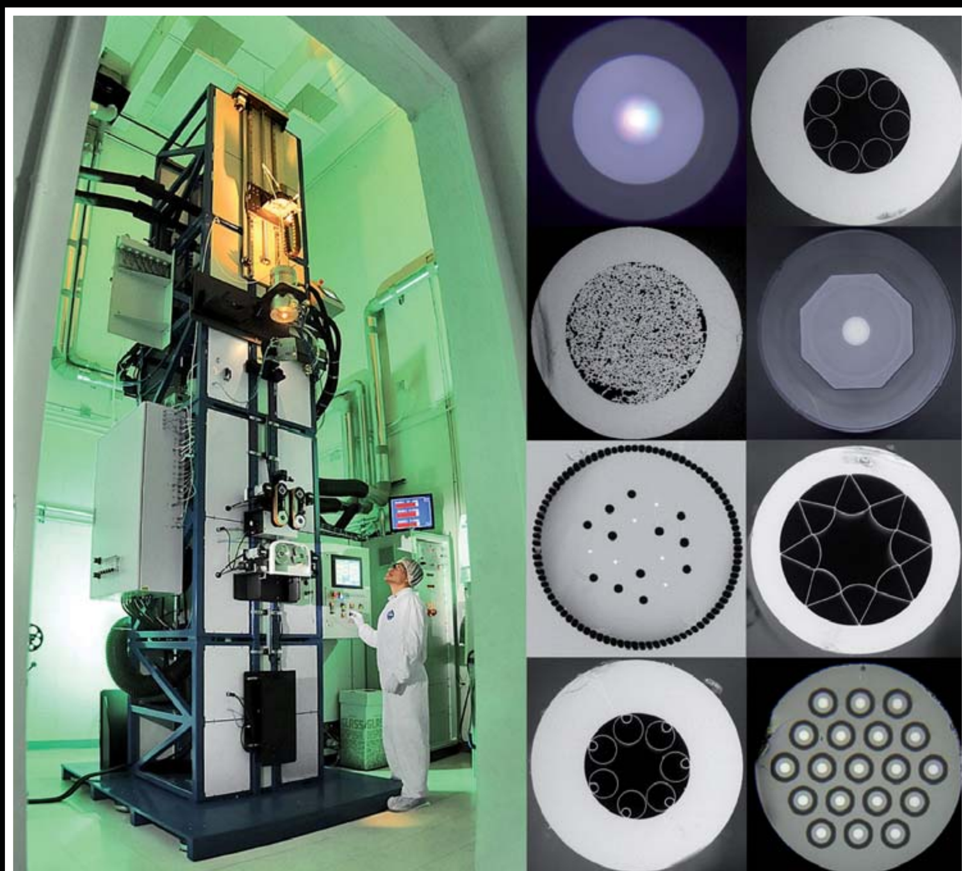

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Research Highlights

Application-Tailored Specialty Optical Fibers

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Abstract—Fiber optics is an integral part of the modern optoelectronic technologies. In particular, specialty optical fibers (SOFs) that are tailored for specific applications can open avenues to novel photonic devices. However, there are only a few academic institutions in the United States that have a strong focus on fiber-optic research and, even fewer, that have the facilities required to fabricate state-of-the-art fibers and prototype devices, based on tailored SOFs. Since 2012, a comprehensive fiber optics facility has been developed at the University of Central Florida within CREOL, The College of Optics & Photonics. The facility is now available to fabricate complex optical fibers within a short timeframe. Here, we present an overview of the fiber facilities at CREOL and a selection of research activities utilizing SOFs in various technology areas.

Index Terms—Optical fibers, optical fiber fabrication, optical fiber communication, optical fiber sensors

Introduction

CREOL, the College of Optics and Photonics at the University of Central Florida in Orlando is one of three academic institutions in the USA with B.S., M.S. and Ph.D. degree programs in photonic science and engineering. Realizing the ever-increasing importance of fiber optics within modern optical technologies and its impact on our daily life, a comprehensive fiber optics research program has been established at CREOL in the past few years. In particular, the installation of a new fiber draw tower in 2012 has enabled scientists and engineers to explore a large parameter space for the design and fabrication of application-tailored specialty optical fibers (SOFs).

Over the last years, this research program has been strongly supported by the U.S. Department of Defense through major grants from the Army Research Office, the Air Force Office of Scientific Research, and the Office of Naval Research in order to provide a strategic resource to make available state-of-the-art optical fibers and fiber-optic components for academic research and industrial applications. In particular, this sponsorship focused on the development, fabrication, characterization, and testing of fibers and fiber optic components for high power lasers and amplifiers.

With increasing proficiency in the fabrication of complex SOFs, there are now a number of small and large businesses that collaborate with the CREOL team on a variety of research and development projects. The applications reach from traditional areas, such as fiber optical communications and fiber optic sensors, to new fields such as fiber-based devices for medical surgery. Our ability to fabricate fibers with complex structures is of key importance for successful research partnerships. Moreover, the impact of the fiber group is even broader due to short prototype fabrication times and the access to many available peripheral resources, such as advanced instrumentation for characterization and testing.

Here, we provide an overview of the fiber fabrication facilities and capabilities at CREOL, as well as a few examples of our research activities exploiting SOFs in the areas of fiber optic communications, high power fiber lasers, and fiber optic sensing.

Fiber optics facilities at creol

During the past 6 years, CREOL has established comprehensive facilities for optical fiber fabrication, characterization, and testing. As its cornerstone, the fiber fabrication laboratory, housed in a high bay area at CREOL, includes a custom-built fiber draw tower, shown in Fig. 1. This draw tower features three different furnaces and a high precision pressure control system. The three different furnaces allow for fiber fabrication from various materials including fused silica and soft glasses within a very large range of glass transition temperatures between 200 °C and 2200 °C. Currently, an advanced modified chemical-vapor deposition (MCVD) system is being installed and will allow us to fabricate optical fiber preforms with tailored index profiles and rare-earth dopant compositions.

Since the commissioning of the facility, we have developed processes and techniques for the fabrication of high-performance SOFs. We have demonstrated photonic crystal fibers, multicore fibers, large mode area fibers with rare-earth doped cores, and a variety of hollow core fibers, to name a few examples.

In addition to the fiber draw tower and the MCVD lathe, we have established a dedicated cleanroom facility for SOF preform manufacturing, including preform assembly rigs and HF etching station. Our glass processing capabilities for fiber preform fabrication, included drilling and grinding with diamond tools as well as glass cutting and polishing tools. Furthermore, we build significant fiber characterization and test capabilities utilizing advanced instrumentation, such as a CO_2 laser based fiber splicing and tapering station, a scanning-electron microscope (SEM) dedicated to fiber analysis during and after fabrication, a high-resolution interferometric refractive index profiler for fibers, a set of spectroscopic instruments for UV to IR wavelengths, a fiber-dispersion measurement setup, and a station to perform detailed fiber mode analyses. Through these investments into facilities, CREOL is one of the US research leaders in advanced optical fiber technology.

Activities in fiber optic communications

The exponentially increasing data traffic in recent years is driving a rapid approach towards the capacity limit of single-mode transmission technologies [1]. This has highlighted the demand for exploring a new physical dimension to multiply the capacity per fiber. Space division multiplexing (SDM), has emerged as a promising approach for dramatically boosting capacity of a single fiber by exploiting multiple modes in multimode fibers

(MMFs) or a number of cores in multicore fibers (MCFs), as independent data channels [1,2]. A compelling advantage of SDM over simply adding parallel channels based in conventional fibers, is its inherent device integration and resource sharing capability. As a result, SDM can multiply link capacity while potentially providing significant benefits in terms of the cost per bit in future telecommunication networks.

As the interest in SDM has gained momentum, rapid progress has been made in fabricating new generations of transmission fibers, examples of these include multicore fibers, coupled-core multicore fibers, precisely engineered MMFs with low differential mode delay (DMD), and ring core fibers, to mention only a few [1–4]. In addition, the implementation of SDM communication systems requires the development of advanced photonic components to support the spatial dimension. In this regard, two critical devices being extensively investigated are SDM amplifiers and spatial mode multiplexers.

Over the past few years, we have successfully demonstrated various SDM fibers and components for exploring new trends in optical communications. Among these, we proposed a seven-core fiber supporting 21 spatial channels in a few-mode multicore configuration, Fig. 2(left). Each core was designed to transmit the first two mode groups (3 spatial modes). Airholes were used to realize a core-to-core crosstalk below −80 $dB\cdot km^{-1}$, enabling a transmission rate of 255 Tbps over 1 km [3]. In an effort to further increase capacity, we fabricated a 19-core MCF with graded index cores profiles optimized for low DMD, see Fig. 2(right). Each core is surrounded by a low-index trench in order to maintain low core-to-core crosstalk levels. In this case, the graded index cores support 6 spatial modes, yielding a total of 114 spatial channels in a fiber of 208 μm outer diameter. The fiber showed good performance for all modes, allowing to significantly multiply the capacity of a single fiber.

Extensive investigations have been dedicated to develop erbium-doped fiber amplifiers (EDFA) suitable for SDM systems [1]. The main challenge is to design MMF amplifiers where all the modes experience the same amount of gain. In general, providing uniform gain among modes is demanding given that signal and pump modes exhibit different profiles and therefore the overlap with the gain medium is mode-dependent. To deal with this problem we have adopted the following strategy: employ an oversized core in order to support a large number of modes and in conjunction use high power cladding pumping. By doing so, we effectively minimize mode-dependent gain (MDG) in a scalable scheme with respect to the number of modes [5]. A microscope image of a 24 μm core MM-EDFA supporting approximately 21 spatial modes with low-MDG of 2 dB is shown in Fig. 3(top). Measured mode profiles at the output of a 1.5 m EDFA covering the mode groups from 1 to 7 before and after amplification are depicted in Fig. 3(top). The intensity profiles clearly indicate negligibly mode mixing and high mode quality.

Coupled-core fibers offer unique possibilities for minimizing mode dependent effects. To explore this idea in an amplifier, we implemented a 4-core EDFA that has strongly coupled cores at both the pump and signal wavelengths [6]. Characterization results confirmed that strong mode-coupling minimizes

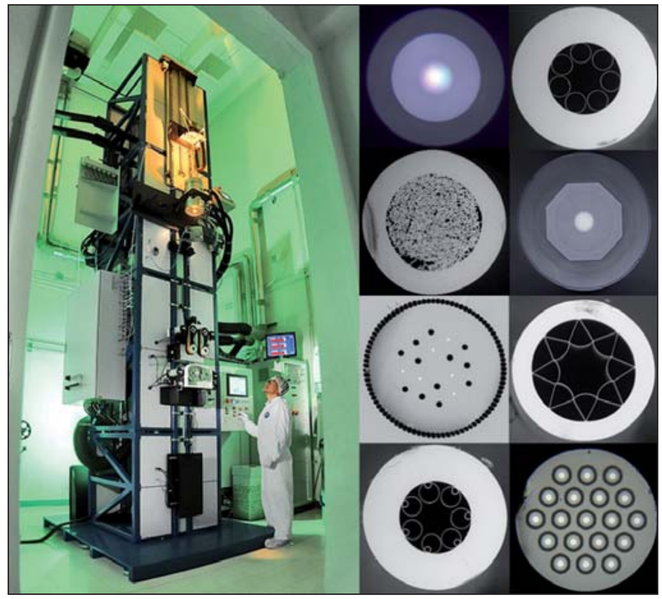

Fig. 1. (Left) CREOL fabrication facility; Fiber draw tower (Right) Microscope images of some SOF fabricated at CREOL.

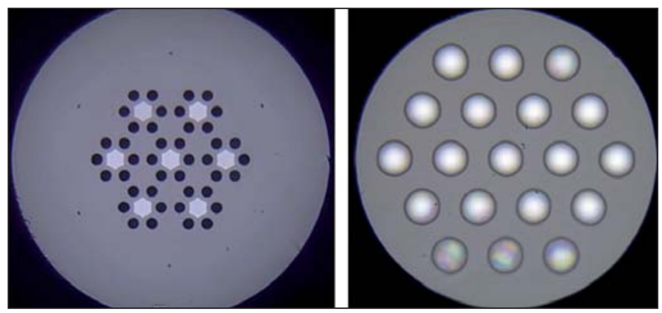

Fig. 2. Microscope images of SDM fibers fabricated at CREOL (left) 7-core hole-assisted MCF (right) MM-MCF.

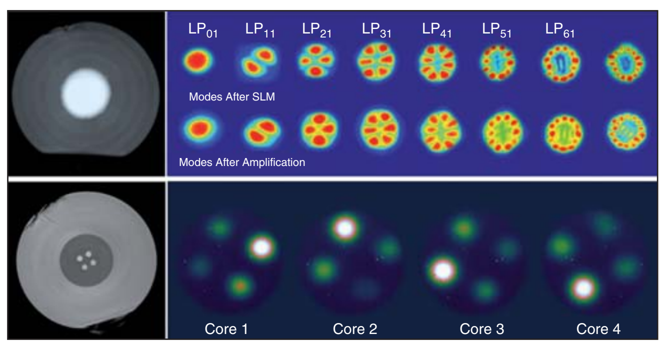

Fig. 3. Microscope images of Er doped fibers fabricated at CREL. (Top) MMF-EDFA, and measured mode profiles before and after amplification. (Bottom) Strongly-coupled core MCF and modes supported by the fiber.

MDG and simplifies requirements on the spatial uniformity of the pump. Fig. 3(bottom) illustrates the end-facet image of the fiber and the measured mode profiles showing coupling between cores.

Besides SDM fibers and amplifiers, mode multiplexers play a fundamental role in SDM systems. The mode multiplexers fabricated at CREOL are all-fiber photonic lanterns [7,8]. A photonic lantern allows one to excite a specific spatial

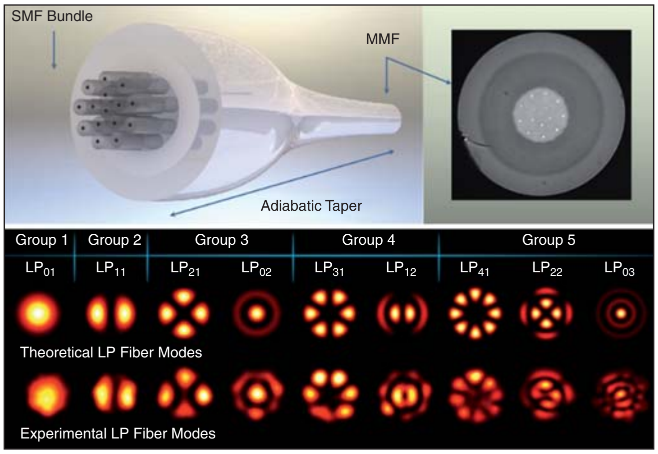

Fig. 4. (top) Schematic of a 15-mode photonic lantern and microscope image of the fabricated device. (bottom) Theoretically expected and experimentally measured modal intensity profiles.

model (or its mode group) in a MMF starting from a single mode fiber, in a low-loss manner. Moreover, it provides seamless integration with the rest of single-mode photonic technologies in telecommunication systems. The schematic and cross-section image of a photonic lantern supporting 15 modes are shown in Fig. 4. The theoretically expected intensity profiles along with the measured near-field distributions of a 15-mode lantern, fabricated in-house, are presented in Fig. 4. The integration of photonic lanterns with advanced multimode transmission fibers has enabled us to demonstrate the scalability of SDM communication links to a large number of spatial-channels [9].

Fibers for high power lasers and amplifiers

With the developments in the last decades of large mode area fibers, high brightness pump diodes, and innovative pumping and laser architectures, phenomenal gains have been made in the efficiency, ruggedness and overall average power (and pulse energy) of fiber lasers. What made this class of solid state lasers so successful, is their remarkable power scalability, excellent beam quality, spectral and temporal versatility, high efficiency and their ability to be integrated into robust and modular systems. As such, fiber lasers with multi-kW average power or MW peak power, capable of producing CW radiation or ultrashort pulses are now readily available.

It is widely recognized that the key to driving fiber laser to levels of performance beyond current achievements rests with increasing the mode area, thereby remaining below the thresholds for damage and nonlinear mechanisms [10,11]. In order to mitigate these undesirable nonlinear effects, extensive investigations have focused on developing advanced large mode area (LMA) fibers that operate in a single-mode fashion. Notable examples of highly specialized LMA fibers include large-pitch fiber (LPF), photonic crystal fiber (PCF), leakage channel fiber, chirally coupled core fiber and bandgap fibers [10,11]. Despite all these advanced waveguide designs, the potential for diffraction limited average power scaling arising from the extraordinary MFD offered by LMA fibers has not materialized. Contrarily, average power scaling of narrow linewidth fiber lasers has unexpectedly hit a barrier attributed to thermo-optic effects [12]. In fact, LMA fibers are prone to waveguide distortions due to thermal energy deposition that can trigger the propagation of undesired higher order modes. Ultimately, these thermally induced refractive index changes lead to the onset of mode instabilities (MI) at high average powers [12]. MI is a threshold-like degradation of the output beam produced by a dynamic power coupling between the fundamental and higher order modes. MI has become by far the most critical limiting factor for average power scaling of fiber lasers with diffraction limited beam quality.

On the other hand, LMA fiber fabrication demands highly specialized manufacturing techniques and high level of process control. In particular, core diameter scaling is restricted by the refractive index accuracy and uniformity of the active glass. Precise control of the refractive index profile is essential for core diameters beyond 30 μm (for ytterbium-doping). Likewise, large index variations must be suppressed to prevent the formation of detrimental guiding elements within the core. These strict constrains rapidly translate into fabrication technological challenges.

The aforementioned challenges highlight the need for academic facilities capable of producing advanced fibers to support the evolution of fiber laser technologies in the years to come. At CREOL, we have developed a fabrication process to accurately control the index profile of ytterbium-doped silica glass suitable for LMA fibers. This has enabled us to demonstrate fibers with ultra-low numerical aperture (NA). A microscope image of an ytterbium-doped LMA with a core diameter of ~40 μm and NA ~0.39, is presented in Fig. 5, along with the measured core refractive index profile. In this fiber, an air-cladding structure is implemented for pump guidance. This design

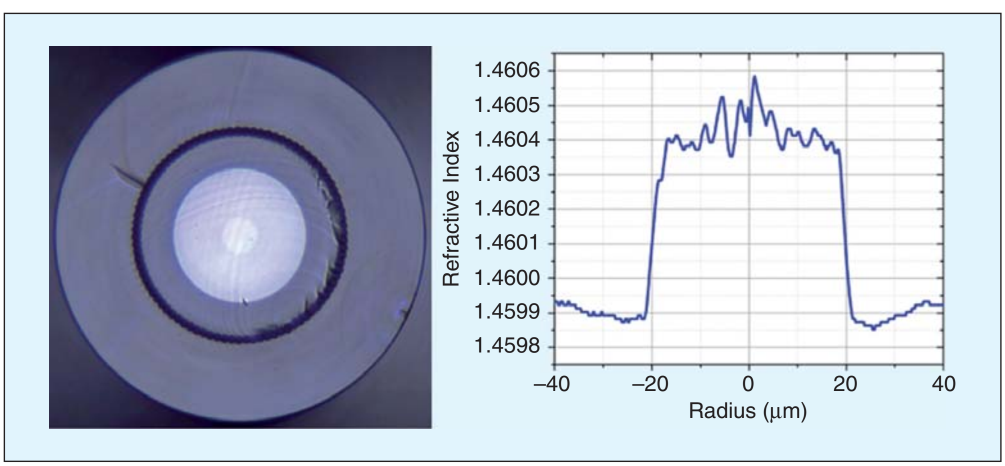

Fig. 5. (left) Microscope image of an ytterbium-doped low-NA fiber and measured refractive index profile of the active core region.

approach guarantees signal guidance while providing mode-selective amplification capabilities. The use of low NA fibers in high power lasers can open up new avenues for MI mitigation, as reducing the NA allows for operation in a close to single mode regime where MI does not take place. As another example, the large pitch ytterbium-doped fiber of ~42 μm core diameter shown in Fig. 5, was fabricated using the well-known stack-and-draw method. In this case, the index of the active core needs to be closely matched to that of the pure silica cladding. Tests of an in-house fabricated, 1 m long rod-type fiber in an amplifier configuration are presented in Fig. 6(right). With 8W seed power, the amplifier provides >7 dB gain at 160 W launched pump and excellent mode quality.

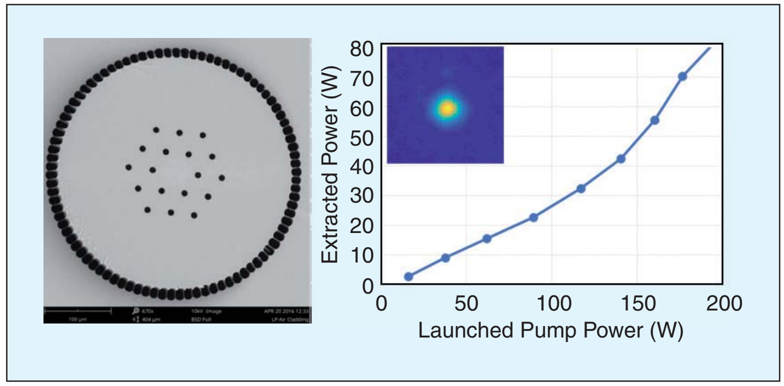

Fig. 6. (left) SEM image of an ytterbium-doped LPF fabricated at CREOL. (right) Typical amplifier performance of a ~1 m long rod-type fiber.

Multicore fiber sensors

Optical fiber sensing is a viable technology to monitor physical parameters such as temperature, force, strain, pressure, and bending to name but a few. Basically, a fiber optic sensor consists of monitoring changes of intensity, phase, or wavelength of the guided light as the fiber is subjected to different environments. There are two fundamentally different categories of fiber optic sensors, distributed and discrete (or point) sensors. The former require sophisticated interrogation systems and are suitable to monitor long distances, on the order of tens of kilometers. Point sensors are simpler and are used in applications that require the monitoring a specific location.

At present, fiber Bragg gratings (FBGs) are the most prominent fiber optic point sensors, widely applied to monitor temperature or strain. Some drawbacks of FBG sensors include their degradation at elevated temperatures above a few hundred degrees Celsius and the need of interrogators with very high spectral resolution. To overcome these limitations many research groups around the world are applying SOFs, for example, photonic crystal fibers or multi-core fibers with isolated cores.

At CREOL, we developed a whole suit of novel fiber optic point sensors based on MCFs with strongly interacting cores [13-16]. Our approach of splicing a few cm-long segment of MCF between two single mode fibers leads to compellingly simple, highly compatible, and cost-effective fiber optic point sensors with excellent performance. The operation principle of these MCF sensors rests upon the interference between supermodes which gives rise to very sharp optical features as illustrated in Fig. 7 for optimized MCF structures [14]. Environmental changes lead to shifts of these interference patterns resulting in high sensitivity to temperature [13] and bending [15], to name two examples. As a major advantage compared to FBG sensors, laboratory experiments demonstrated that these MCF sensors can operate over hours at elevated temperatures up to 1000 °C. In addition, multi-parameter sensing has been shown [16].

Recently, the MCF sensors were transferred into field trials, to evaluate their performance in deployment conditions [16]. We tested and calibrated our sensors in a high-fidelity aerospace test laboratory. Moreover, some sensors were carefully packaged and used to monitor strain in a cross-beam of the Vizcaya Bridge between Portugalete and Getxo (a UNESCO World Heritage Site) during a three months period. In all the experiments the MCF sensors were compared with commercial strain gauges and FBG sensors. The results shown in Fig. 9 indicate the same level of sensitivity can be achieved with MCF sensors when measuring the strain induced by the passing gondola moving along the bridge between the two cities. Our results suggest that the introduced MCF sensing technology is likely to reach a high readiness level to compete with state-of-the-art fiber sensors. Combining their high performance, as shown by the measurements performed at the Vizcaya bridge, with their

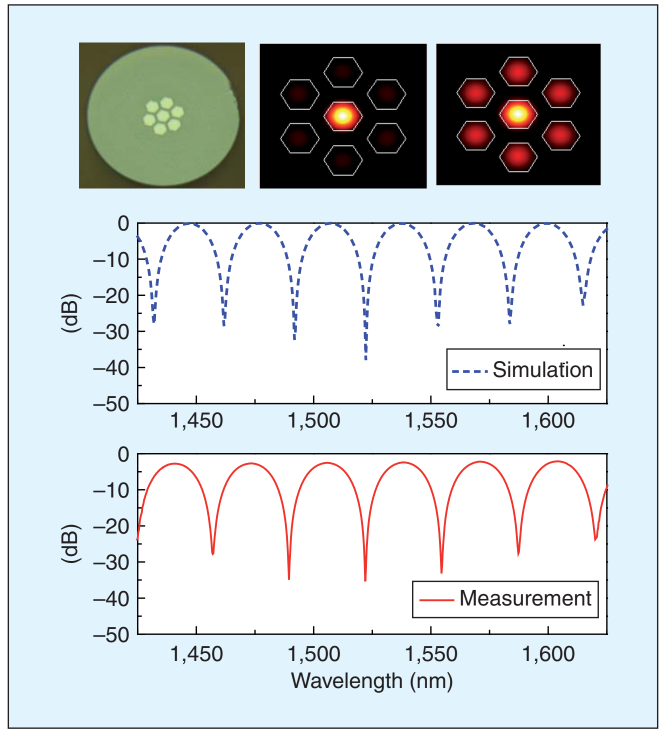

Fig. 7. (top) Microscope image of a 7-core fiber facet (outer diameter = 125 mm) and simulated supermodes that are excited by launching light from a centrally aligned single mode fiber. (bottom) Simulated and measured transmission spectra through a chain of single mode fiber—MCF—single mode fiber with a 2 cm-long MCF segment [14].

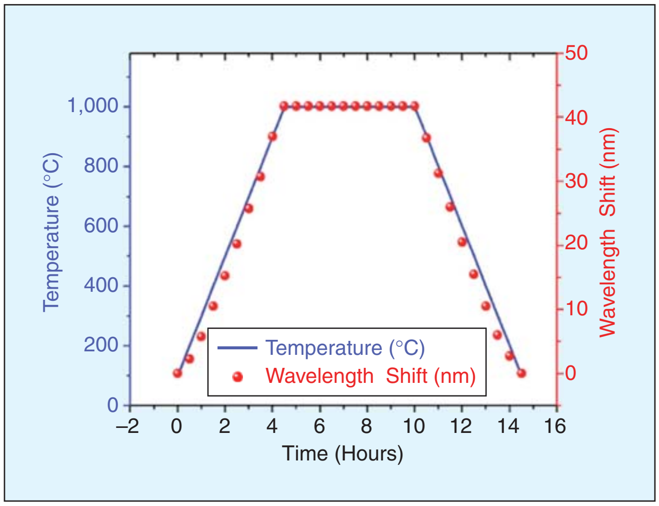

Fig. 8. Wavelength shift at temperatures between 100 °C and 1000 °C measured over a period of more than 14 hours [13].

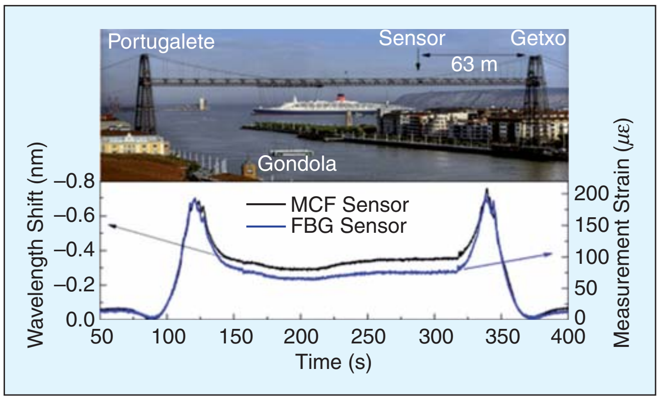

Fig. 9. Photograph of the Vizcaya Bridge highlighting the position of the sensor and the hanging gondola. The graph shows the shift of the interference pattern of the MCF sensor and the strain measured by an FBG sensor at the same point of the cross-beam of the bridge while the gondola moves from Portugalete to Getxo and back. At times of about 125 s and 340 s the gondola passed the sensor position [16]. Tests performed by Villatoro's group, Universidad del Pais Vasco.

compact packaging and the possibility of operation at elevated temperatures, MCF sensors could open new avenues and markets fiber point sensors.

Outlook:

In order to support the exponentially growing bandwidth demand in optical networks, CREOL will continue exploring novel SDM technologies which can enable a significant increase of capacity. High power fiber lasers, will also be developed by CREOL research staff and students using our world-class facilities.

The broader impact of CREOL fiber facility is educating students that will drive tomorrow's advancements in fiber optics systems and engineering. Moreover, by establishing research partnerships with innovative optoelectronic business, we expect to support our partners with the prototyping of specialty fibers and devices in order to develop new technologies in areas including lasers, medical, sensors and communications.

Acknowledgement

This work was supported by Army Research Office, ARO (W911NF-13-1-0283, W911NF-15-1-0338 and W911NF-12-1-0450) and Air Force Office of Scientific Research, AFOSR (FA9550-15-10041 and FA2386-13-1-3019).

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