Microfiber Knot Resonators as Sensors
A Review

André D. Gomes and Orlando Frazão
INESC TEC and Department of Physics and Astronomy, Faculty of Sciences, University of Porto, Rua do Campo Alegre 687, 4150-179 Porto, Portugal

Keywords: Microfiber Knot Resonator, Temperature Sensor, Refractive Index Sensor, Coated Microfiber Knot Resonator.

Abstract: Microfiber knot resonators find application in many different fields of action, of which an important one is the optical sensing. The large evanescent field of light can interact and sense the external medium, tuning the resonance conditions of the structure. The resonant property of microfiber knot resonators can also provide, in some cases, an enhancement in the sensing capability. Until nowadays, a wide variety of physical and chemical parameters have been possible to measure with this device. New developments and improvements are still being done in this field. A review on microfiber knot resonators as sensors is presented, with particular emphasis on their application as temperature and refractive index sensors. The properties of these structures are analyzed and different assembling configurations are presented. Important aspects in terms of the sensor stability are discussed, as well as alternatives to increase the sensor robustness. In terms of new advances, an overview on coated microfiber knot resonators is also presented. Finally, other microfiber knot configurations are explored and discussed.

1 INTRODUCTION

Over the last few decades, optical fiber sensing proved to be one of the most powerful and successful application of both optical fibers and sensing technology (Lou, Wang, and Tong, 2014). In fact, with the developments and the advances of the telecommunication industry, optical fibers begun to be a subject of intense investigation. With this outbreak, their application to various sensing fields were widely explored until nowadays.

From the combination of optical fibers and nanotechnology, the fabrication of micro and nanofibers (MNF) by tapering a fiber to micrometric or even nanometric size has led optical fiber sensing to another level (Lou et al., 2014).

Until nowadays, new sensing configurations based on MNFs were studied and developed. These type of sensors come in many different forms and normally the measured effects are sensed via intensity or phase change of the transmitted light. One of the configurations are the resonator-type MNF structures, which use resonant structures such as loop resonators, knot resonators or coil resonators.

Microfiber knot resonators (MKR) are one of the configurations that had a huge impact, not only in the field of sensing, but also in other fields such as, for example, ultrafast optics, due to its high quality factor (Q-factor) (Yi-ping Xu et al., 2015). These structures are easy to fabricate and more stable compared, for instance, with microfiber loop resonators. In the last years, refractive index and temperature sensing using MKR configurations were demonstrated.

Here we review the recent progress in microfiber knot resonator as sensors, mainly for refractive index and temperature sensing applications, as well as new configurations of this structure. The sensor stability is also discussed.

2 PROPERTIES OF MICROFIBER KNOT RESONATORS

A microfiber knot resonator consists in tying a knot in the taper waist region of a MNF, allowing coupling and evanescent overlap between modes propagating in adjacent turns. Light that enters the MKR will be split in the knot region between the ring and the

Gomes A. and FrazÃčo O.
Microfiber Knot Resonators as Sensors - A Review.
DOI: 10.5220/0006264803560364

output. New light that enters the MKR will combine with light going to the output of the structure, while feeding at the same time the ring. To create the MKR, first, the freestanding end of a MNF is assembled into a large ring with few millimeters in diameter. Then, the diameter of the ring is progressively reduced by pulling the free end of the MNF until a microknot with the desired dimensions is obtained (Figure 1). This overlap of the fiber with itself allows no need for a precise alignment (Xiao and Birks, 2011). The small-size and low fabrication cost of these structures have attracted much attention to produce them for sensing purposes (G. Chen and Ding, 2013).

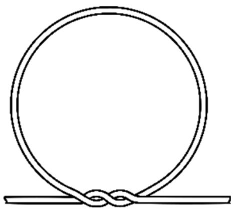

Figure 1: Schematic of a MKR. The structure is produced using a taper.

2.1 Properties/Parameters

MKRs have interesting properties: high quality factor and finesse, and a free spectral range (FSR) that depends on the diameter of the ring. The schematic of a high-Q MKR transmission spectrum is presented in figure 2.

The quality factor (Q) is a useful quantity to evaluate the losses of the resonator. The higher the Q-factor, the longer the light stays in the ring. This factor can be expressed as (Brambilla et al., 2009):

$$Q = \frac{\lambda_{res}}{FWHM} \quad (1)$$

where λ_{res} is the resonance wavelength and $FWHM$ is the full width at half-maximum. MKRs can achieve Q factors up to 10^5 (De Freitas, Birks, and Rollings, 2015; X. Jiang, Tong, et al., 2006; Xiao and Birks, 2011).

The finesse is also a measure of the resonator losses but it is independent of the resonator length. It is defined as:

$$F = \frac{FSR}{FWHM} \quad (2)$$

The FSR of a microfiber knot resonator, which is the distance between two adjacent resonance wavelengths λ_1 and λ_2, is given by:

$$FSR \approx \frac{\lambda_1 \lambda_2}{n_{eff} L} \quad (3)$$

where n_{eff} is the effective refractive index of the microfiber and L is the cavity length. In an MKR, the cavity length is given by the perimeter of the ring. This property is very useful since one can tune the FSR of the sensor by adjusting the diameter of the MKR.

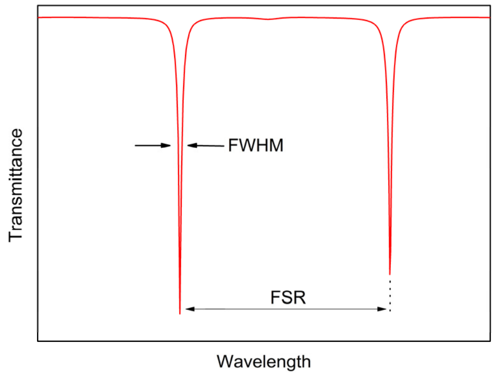

Figure 2: Schematic of a MKR transmission spectrum.

2.2 Assembling Configurations

Most of the reported configurations assemble MKR using a MNF with a freestanding end (like a pigtail) and use a second microfiber (output fiber) to collect the light transmitted out of the knot, as depicted in figure 3. The microfiber is evanescently coupled to the output fiber of the MKR, connected through Van der Wall attraction. This solution presents some limitations in terms of applications of the MKRs. Despite some authors claim that MKRs assembled from double-ended MNFs can easily break when knotted (Brambilla et al., 2009; X. Jiang, Tong, et al., 2006; X. D. Jiang, Chen, Vienne, and Tong, 2007), Xiao et al. demonstrated the first MKR made from double-ended tapered fibers, back in 2011 (Xiao and Birks, 2011). The authors achieved MKRs with high finesse (104) using a 128 µm-diameter MKR assembled from a 1 µm-diameter fiber taper. A high Q-factor of 97260 was also obtained for a 570 µm-diameter MKR assembled from the same fiber taper. The minimum MKR diameter achieved was 46 µm using the same fiber taper.

Also in 2011, the first all-fiber and optically tunable MKR has been proposed (Chen et al., 2011). The MKR was coated with a photoresponsive liquid crystal mixture which presents an easily variable RI that can be changed upon irradiation with UV light. The change in the MKR effective refractive index caused by the liquid crystal induces a change in the resonance wavelengths. A 0.15 nm spectral shift was observed when irradiating a 468 µm-diameter MKR with 50mW/cm^3 of UV light. The MKR was assembled from a 2.5 µm-diameter fiber taper. The reversibility of the process is shown to be a great advantage of this technique.

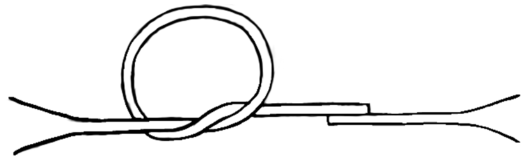

Figure 3: Schematic of a MKR using a second microfiber as collecting fiber.

2.3 Stability

The stability of the MKR can be increased using different methods or techniques. The first consists in integrating the structure on a polished solid MgF_2 crystal substrate that helps to support the MKR. Since the MgF_2 substrate presents low refractive index (n=1.37), the MKR resonance is maintained (X. Jiang, Yang, et al., 2006; Li and Ding, 2014; Y. Wu, Rao, Chen, and Gong, 2009), despite a small change in the resonance wavelengths due to a change in the effective refractive index. This substrate also provides good thermal conductivity which is helpful for temperature measurements (Y. Wu, Rao, et al., 2009).

Another common way to achieve long-term stability is to coat the MKR with low refractive index polymers (Li and Ding, 2014; Zeng, Wu, Hou, Bai, and Yang, 2009), or simply use MKRs made out of polymer microfibers (Y. Wu, Rao, et al., 2009; Y. Wu, Zhang, Rao, and Gong, 2011; H. Yu et al., 2014). Regarding this method, Vienne *et al.* performed an analysis on the effect of host polymers in microfiber knot resonators (Vienne, Li, and Tong, 2007). The FSR and the maximum Q-factor and extinction ratio did not change significantly after coating the MKR with low-index polymer. However, the wavelength region of high Q-factor and extinction ratio shifts when the polymer coating is applied. Polymer coatings allow to fix the knot structure, reducing the probability of changing the MKR diameter. Li *et al.* explored the optical degradation of a MKR over time (Li and Ding, 2014). In fact, the transmission losses of a bare MKR increased at the speed of around 0.24 dB/h, reaching 18 dB after 3 days, unlike a Teflon coated MKR where no change was noticed for half a month. This result shows that Teflon coating (n~1.31) provides protection against degradation over time.

In 2011, a MKR was embedded in hydrophobic aerogel (n~1.05) (Xiao and Birks, 2011). The losses of the structure off-resonance (0.75 dB) proved to be much lower than other encapsulants. Due to the low refractive index, the aerogel avoids the reduction of light confinment and change of dispersion when compared with low-index polymers.

Robustness and resistance can also be gained using large knots made out of larger diameter fibers (Gomes and Frazão, 2016). However, the resonance property can be lost due to the small evanescent field of light.

3 SENSING WITH MICROFIBER KNOT RESONATORS

Microfiber knot resonators can be used to sense a wide variety of physical, chemical, and biochemical parameters. A more detailed analysis of some published results will now be made regarding mainly the use of MKRs for temperature and refractive index sensing.

3.1 Temperature Sensing

Temperature variations around a microfiber knot resonator will change its length and refractive index, resulting in a shift of the resonance wavelengths (Zeng et al., 2009). By monitoring the resonance wavelength variations one can have information about the temperature variations around the sensor. Using this principle of working, many MKRs have been proposed for temperature sensing.

Wu *et al.* reported two temperature sensors based on silica/polymer MKR (Y. Wu, Rao, et al., 2009). Both sensors were placed in an MgF_2 crystal plate and covered with an MgF_2 slab to make them more robust and immune to environmental fluctuations, as shown in figure 4. Moreover, the MgF_2 substrate ensures good thermal conductivity and presents low refractive index, as discussed back in section 2.3.

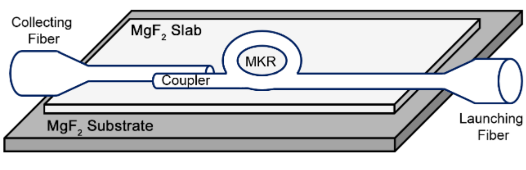

Figure 4: Schematic of the MKR temperature sensors presented by Wu *et al.*

For the silica MKR, a 1.7 µm-diameter silica fiber taper was used to create a 190 µm-diameter MKR.

The structure presents a Q-factor of 12000. A temperature sensitivity of around 52 pm/ºC was obtained between 30 ºC to 700 ºC. For the case of a polymer MKR, a 2.1 µm-diameter PMMA fiber (n~1.49) was used to produce a 98 µm-diameter polymer MKR. Polymer microfibers have the advantage of bending more easily and with smaller radius of curvature than standard silica microfibers. The structure presents a Q-factor of 8000, lower than the silica MKR. However, in terms of temperature sensing a sensitivity of 266 pm/ºC was achieved between 20 ºC and 80 ºC. PMMA present higher thermal expansion and thermal-optical coefficient (TOC) than silica, therefore polymer MKRs exhibit more temperature sensitivity than silica MKRs. Despite have higher sensitivity, the measuring range of the polymer MKR is lower than the silica MKR due to the low melting point of the polymer.

Also in 2009, Zeng *et al.* presented a polymer coated MKR for temperature sensing (Zeng et al., 2009). The assembling of the sensor is similar to the one presented in figure 4 but with some modifications. Instead of an MgF_2 substrate, a glass plate was adopted as substrate due to its good adhesion ability to the polymer. A 20 µm thin layer of low refractive index polymer (EFIRON UVF PC-373, n=1.3759 at 852 nm) was coated on the surface of the substrate to isolate the MKR from the high refractive index of the glass plate. To fabricate the MKR, a 1 µm-diameter fiber taper was used to produce a 55 µm-diameter MKR. A second polymer layer was coated above the MKR to make it immune to environmental changes. The authors obtained 270 pm/ºC for the temperature sensitivity in the heating process from 28 ºC to 140 ºC, and -280 pm/ºC for the temperature sensitivity in the cooling process from 135 ºC to 25 ºC. These values are similar to the PMMA MKR temperature sensitivity demonstrated by Wu *et al.* The reported resolution for this sensor is 0.5 ºC, although it can be increased if a higher resolution spectrometer is used.

Later in 2014, a simple silica MKR was theoretically an experimentally studied for seawater temperature sensing by Yang *et al*. (Yang, Wang, Wang, Liao, and Wang, 2014). Measuring seawater temperature can be a little tricky since silica and seawater show opposite thermal-optical coefficients. So, when the TOC of silica is predominant the resonant wavelengths with suffer a red shift, while in the case of a predominance of the seawater TOC, a blue shift is observed. Theoretically, there is a fiber diameter for which the effect of silica TOC and seawater TOC will cancel each other. This happens for a 1.27 µm-diameter fiber taper. Bellow that diameter the temperature sensitivity will be negative, and above that value the temperature sensitivity will be positive, saturating for fiber tapers with diameters above 4 µm. Furthermore, the sensitivity will also increase if the probing wavelength is increased. In terms of experimental results, a maximum temperature sensitivity of 22.81 pm/ºC was achieved from 23 ºC to 33 ºC using a 473 µm-diameter MKR produced from a 3.91 µm-diameter fiber taper. The value was obtained with a probing wavelength of 1599.6 nm. The sensor presents a Q-factor of 3000 and a finesse of 11.69.

Still for temperature sensing, a configuration based on a microfiber double-knot resonator was developed for multi-point sensing by Wu *et al.* (Y. Wu, Jia, Zhang, Rao, and Gong, 2012). The sensor consists of producing two MKRs and then couple both structures using the free-end of each MKR. A schematic of the sensor is depicted in figure 5. The two created knots, one with 506 µm-diameter and the other with 500 µm-diameter, were fabricated from a 2.3 µm-diameter fiber taper. The distance between the knots can be tuned by adjusting the length of the coupling region.

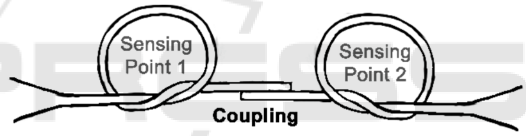

Figure 5: Schematic of the microfiber double-knot resonator in series.

If the diameter of both knots is the same (same loop length), the interference spectrum shows a regular resonance like a single MKR. On the other hand, if now one of the diameters changes a new phase matching condition will arise. In other words, a second-order resonant peak will appear between the primary resonant peaks. The authors demonstrate that if the temperature changes locally on the first MKR, only the primary resonant peak will shift while the second-order resonant peak is constant. In the same case, if the temperature of the second MKR changes, the second-order resonant peak will shift while the primary resonant peak is constant. With this, multi-point temperature sensing is achieved in a very small scale.

3.2 Refractive Index Sensing

Refractive index sensing using microfiber knot resonators consists mainly of taking advantage of the large evanescent field, which can interact with the external environment. Variations in the external medium refractive index will change the light properties, which leads to a change in the MKR resonance conditions. This effect is manifested as a shift in the resonance wavelengths and in a change in the FSR that are proportional to the external refractive index variations.

Li *et al.* developed a Teflon coated MKR (n_{Teflon}~1.31) for refractive index sensing (Li and Ding, 2014). To apply the polymer a dip-coating technique was used, whose process is outlined in figure 6. To produce the sensor, a microfiber with an initial diameter of 2.92 µm was used to create a 1.02 mm-diameter MKR. After the coating process, the microfiber diameter increased to 3.95 µm, allowing to estimate a value of 0.5 µm for the Teflon thickness. The MKR diameter after coated was reduced to around 0.45 mm due to tensions suffered during the dip-coating process. A Q-factor of 20000 was obtained for the MKR structure before coating, increasing to around 31000 after the Teflon coating. A sensitivity of approximately 30.5 nm/RIU was reported for this sensor in the refractive range of 1.3322 to 1.3412.

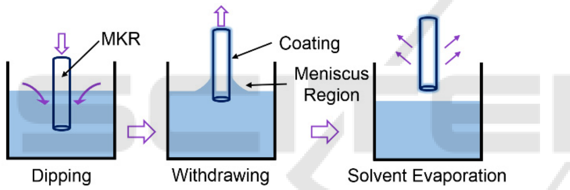

Figure 6: Illustration of the MKR dip-coat process in Teflon.

Before that, Lim et al. proposed a MKR with around 0.5 mm diameter in a Sagnac loop reflector configuration (Lim et al., 2012). The Sagnac loop reflector configuration allows the signal to be collected through the incident path. The microfiber structure was embedded in low refractive index Teflon (n~1.31), except the MKR sensing region, to obtain a balance between responsiveness and robustness. A schematic of the experimental setup is depicted in figure 7.

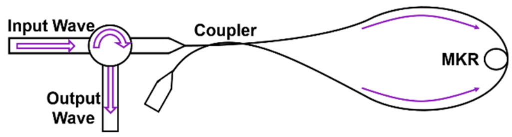

Figure 7: Schematic diagram of a MKR in a Sagnac loop reflector.

For the sensor, a sensitivity of 30.49 nm/RIU was obtained in a refractive index range from 1.334 to 1.348. This value of sensitivity is very similar to the previously analysed Teflon coated MKR proposed by Li *et al.* In terms of temperature response, the sensor shows a sensitivity of 20.6 pm/ºC between 30 ºC and 130 ºC.

More recently, Yu et al. reported a polymer MKR for refractive index sensing (H. Yu et al., 2014). A microfiber of Poly(trimethylene terephthalate) (PTT) was produced with 1.3 µm-diameter. PPT has strong flexibility, large refractive index (n=1.638) and presents good transparency in the visible and near-infrared spectrum. A MKR with 85 µm-diameter was created from the PPT microfiber and placed on an MgF_2-coated glass substrate. A Q-factor of 11000 was obtained. The sensor was analyzed under different mixtures of water and glycerol at different concentrations. The structure shows two different linear regimes: a refractive index sensitivity of 46.5 nm/RIU for low concentration solutions (1.35-1.38) with a resolution 4.3×10^{-5} RIU, and a refractive index sensitivity of 95.5 nm/RIU for high concentration solutions (1.39-1.41) with a resolution of 2.1×10^{-5} RIU.

3.3 Other Sensing Applications

Microfiber knot resonators can also be applied for sensing many other types of parameters. For example, Wu *et al.* proposed the first MKR used for acceleration sensing by optically interrogating the vibration of a microelectromechanical system (MEMS) (Y. Wu, Zeng, et al., 2009). They used a 1.1 µm-diameter fiber taper to create a 386 µm-diameter MKR with a Q-factor of 8500. The MKR is placed at the top surface of a MEMS cantilever. When acceleration is applied to the system, the MKR will experience strain, producing a shift in the resonant wavelength. Monitoring the detected intensity, a sensitivity of 654 mV/g was achieved in a dynamic range of 20 g. In terms of wavelength shift, this sensitivity is 29 pm/g. The resolution of this system is 80 µg/$\sqrt{Hz}$ at 300 Hz.

In 2015, the first underwater acoustic sensor using MKR was reported by Freitas *et al.* (De Freitas et al., 2015). The authors use a 4 µm-diameter fiber taper to produce an 800 µm-diameter MKR. The sensor encapsulation of the sensor is made by placing the MKR in a polytetrafluorethylene (PTFE) tray and embedded in silicone rubber. A Q-factor of 41100 was achieved for this structure, being the highest Q-factor obtained until that point for an encapsulated MKR. Acoustic wavefields will change the external pressure, causing variations in the MKR optical path length, as well as changes in the fiber refractive index due to elasto-optic effects. A normalized sensitivity,

$\left(\frac{\delta\lambda}{\delta p}\right)/\lambda$, of -288 dB re/µPa was obtained using acoustic frequencies from 25 Hz to 300 Hz. Alternatively, the sensitivity can be expressed as 5.83×10^{-3} pm/Pa. For this system, a fast spectrometer is needed to pick the transmission spectrum as it changes in time.

MKRs can also be used for salinity sensing, which is somehow similar to refractive index sensing. Liao *et al.* presented a MKR for sensing the concentration of NaCl in solution (Liao, Wang, Yang, Wang, and Wang, 2015). Fiber tapers with diameters from 3.5 to 2.5 µm were used to make 855 µm-diameter MKRs. A maximum sensitivity of 21.18 pm/% was achieved in the range of 20.494% to 37.178%, with a probing wavelength of 1600 nm.

A relative humidity sensor using MKRs was proposed in 2014 (Gouveia, Pellegrini, dos Santos, Raimundo, and Cordeiro, 2014). A 150 µm-diameter MKR was produced from a 3 µm-diameter fiber taper. The structure was coated with Nafion. Nafion is a perfluorosulfonated-based polymer which presents high hydrophilicity, chemical and thermal stability, high conductivity, high adherence to silica, and also mechanical toughness. The sensor shows two regimes, one for low humidity (30 to 45% relative humidity (RH)) where a maximum sensitivity of (0.11±0.02) nm/% RH is obtained, and other for higher-mid humidity (45 to 75% RH) where the maximum sensitivity is (0.29±0.01) nm/%.

4 RECENT DEVELOPMENTS IN COATED MICROFIBER KNOT RESONATORS

More recently, the aim of the researchers has been to incorporate other materials in the microfiber knot resonators in order to achieve new devices with enhanced sensitivity to the measured parameters. The idea is to take advantage of the material and the MKR resonant property to boost the sensor response.

In 2015, a palladium-coated MKR was presented for enhanced hydrogen sensing (X. Wu, Gu, and Zeng, 2015). Palladium (Pd) has been studied for hydrogen sensing applications due to its highly selective and reversible absorption of hydrogen (Hübert, Boon-Brett, Black, and Banach, 2011; Silva, Coelho, Frazão, Santos, and Malcata, 2012; Wadell, Syrenova, and Langhammer, 2014). Since Pd coatings are very thin (less than 1 µm), the interaction between the confined light in optical fiber and the Pd coating is insufficient. However, the proposed sensor takes advantage of the MKR to enhance the interaction of light with the Pd coating. In fact, due to the recirculation of resonant light in the MKR, the interaction of light with the Pd coating will accumulate each time light travels another turn in the MKR. This cumulative effect enhances the sensor sensitivity while using just small interaction lengths and a thin Pd film (~13 nm-thick), compared with other existing optical fiber hydrogen sensors. The Pd coating was performed using a plasma sputtering device in a vacuum chamber and the hydrogen concentration was monitored by measuring the shift and the absorption at a resonant wavelength.

More recently, the deposition of graphene oxide (GO) in MKR was studied for gas sensing, such as NH_3 and CO (C.-B. Yu et al., 2016). The refractive index of GO is modified when gas molecules are adsorbed on its surface. Hence, depending on the concentration of gas molecules, the refractive index of the GO film will change. The sensor is composed of a 1.85 mm-diameter MKR, made out of a 5.1 µm-diameter fiber taper, placed over an MgF_2 structure, and covered with a GO sheet. To form the GO film, a droplet of a 100 mg/L GO solution was dropped onto the knot and heated up (~40 ºC) until it was dried. A Q-factor of 78000 was achieved without the GO sheet, which was reduced to 49000 after depositing the GO. The sensing structure was used to monitor carbon monoxide (CO) and ammonia (NH_3) concentrations. A CO sensitivity of ~0.17 pm/ppm and a NH_3 sensitivity of ~0.35 pm/ppm were obtained for concentrations bellow 150 ppm.

5 OTHER CONFIGURATIONS

In addition to the normal microfiber knot resonator structure, new ways of producing different MKRs were also explored in the last years. One of those configurations is the reef knot microfiber resonator demonstrated by Vienne *et al.* (Vienne et al., 2009). The reef knot was fabricated using 2 microfibers, a 1.2 µm-diameter biconical taper and a 1.5 µm-diameter taper with a free end, as depicted in figure 8.

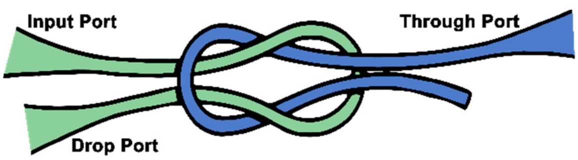

Figure 8: Schematic of a reef knot microfiber resonator.

Table 1: Comparison between different reported configurations for temperature sensing.

Work	Configuration	Q-Factor	Sensitivity	Range
(Lim et al., 2012)	MKR in Sagnac Loop Reflector	X	20.6 pm/ºC	30ºC – 130ºC
(Yang et al., 2014)	Simple Silica MKR (for Seawater)	3000	22.81 pm/ºC	23ºC – 33ºC
(Y. Wu, Rao, et al., 2009)	Silica MKR with MgF_2 slab	12000	52 pm/ºC	30ºC – 700ºC
(Y. Wu, Rao, et al., 2009)	Polymer (PMMA) MKR	8000	266 pm/ºC	20ºC – 80ºC
(Zeng et al., 2009)	Polymer (EFIRON) MKR	X	270 pm/ºC (Heating)	28ºC – 140ºC
---	---	X	-280 pm/ºC (Cooling)	135ºC – 25ºC

Table 2: Comparison between different reported configurations for refractive index sensing.

Work	Configuration	Q-Factor	Sensitivity	Range
(Li and Ding, 2014)	Teflon coated MKR	31000	30.5 nm/RIU	1.3322 – 1.3412
(Lim et al., 2012)	MKR in Sagnac Loop Reflector	X	30.49 nm/RIU	1.334 – 1.348
(H. Yu et al., 2014)	Polymer (PTT) MKR	11000	46.5 nm/RIU	1.35 – 1.38
---	---	---	95.5 nm/RIU	1.39 – 1.41
(Z. Xu et al., 2015)	Cascaded MKR	X	6523 nm/RIU	1.3320 – 1.3350

To produce the structure, the biconical taper is bent in a "U" form and the free standing end of the second taper is guided through the first taper, also in a "U" shape, forming the reef knot. A non-circular reef knot was created with 340 µm-diameter in the short axis and 450 µm-diameter in the long axis. A Q-factor of 10000 was achieved for the "through" port and 3500 for the "drop" port. This device can be used as an add-drop filter.

In 2015, a microfiber double-knot resonator with a Sagnac loop reflector was proposed (Yiping Xu et al., 2015). The difference between this double-knot resonator and the one explored back in section 3.1 is the location of the second knot.

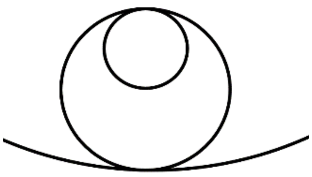

Figure 9: Schematic of a microfiber double-knot resonator in parallel.

In this case, the same microfiber is used to create two knots, being the second knot is inside the first one, as shown in figure 9. A Sagnac loop is created in the end of the resonator so that light can experience the double-knot structure twice, enhancing the response, and also returning from the input port allowing to monitor the sensor in reflection. The transmission spectrum of a double-knot in parallel is not the overlap of the transmission spectrum of each knot independently, just as it happens with the double-knot in series (Yiping Xu et al., 2014).

Xu *et al.* created an interesting small-size refractometer for detecting slight refractive index variations based on cascaded microfiber knot resonators (CMKR) with Vernier effect (Z. Xu et al., 2015). The Vernier effect is commonly used in calipers and barometers to enhance the measurement accuracy through the overlap between lines on two scales with different periods. In this case, the setup uses two MKR with millimeters of diameter (1.178 mm and 1.230 mm) assembled from a microfiber of 1.9 µm diameter. An illustration of the used configuration is presented i\n figure 10.

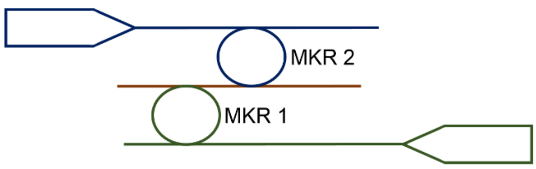

Figure 10: Schematic of a cascaded microfiber resonator.

In the experiment, the ambient RI of the first MKR is kept constant (1.3315), while the ambient RI of the second MKR is slightly varying. The wavelength shift due to the RI change was measured and a sensitivity of 6523 nm/RIU was obtained. This sensor allows a resolution of 1.533×10^{-7} RIU because the measured wavelength shift is an absolute parameter dependent on the relative optical intensity variation. So, relative intensity noise in the light source, thermal noise and shot noise in the photo-detector of the spectrum analyzer do not affect the RI detection. Furthermore, if the first MKR is embedded in a low RI polymer, such as Teflon, it increases its robustness and long-term stability, ensuring the first MKR to be immune to ambient RI changes.

Recently, a Mach-Zehnder interferometer (MZI) with a MKR was proposed for simultaneous measurement of seawater temperature and salinity (Liao, Wang, Wang, Yang, and Wang, 2016). Two microfibers, the first with 2.8 µm-diameter and the second one with 3.3 µm-diameter, were used to produce the sensor. The thinner fiber was used to create the MKR and the thicker fiber was used to form the second arm of the interferometer, creating the structure depicted in figure 11.

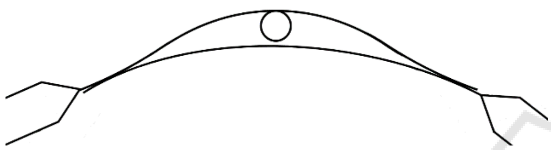

Figure 11: Schematic of a MZI with a knot resonator.

The transmission spectrum of the structure is a combined response of the MZI and the MKR. A temperature sensitivity of -112.33 pm/ºC and 13.96 pm/ºC was achieved for the interference peak and the resonant peak respectively, from 13.7 ºC to 25 ºC. In terms of salinity, sensitivities of 208.63 pm/‰ and 16.21 pm/‰ were obtained for the interference peak and the resonant peak, respectively, between 25 ‰ and 37 ‰. Using these values, a matrix method can be used to discriminate between temperature and salinity.

6 CONCLUSIONS

So far, a great diversity of microfiber knot resonators have been proposed and demonstrated for numerous sensing applications. From these applications, the temperature and refractive index sensing using microfiber knot resonators were the subject of several studies. A comparison between the different microfiber knot resonator configurations discussed previously is summarized in table 1 for temperature sensing and in table 2 for refractive index sensing. Microfiber knot resonators present many characteristics (small size, fast-response, high-Q, robustness, low cost, among others) which can be an advantage over some conventional sensors. Moreover, the ease of incorporating different materials in microfiber knot resonator, such as various low index polymers, aerogels, or even materials like palladium and graphene oxide, reveals great potential for new applications and for expanding of the scope of these structures.

In the last years, the aim of the researchers has been to explore and develop new microfiber knot resonator configurations, as well as to incorporate materials in microfiber knot resonators in order to achieve new devices with enhanced sensitivity to the measured parameters.

As a future outlook, we believe that the incorporation of new materials in microfiber knot resonators is a field that will continue to be developed. Another field to be explored is the combination of microfiber knot resonators with other well-known structures (interferometers, Bragg gratings, Fabry-Perot cavities) with the objective of obtain new sensors with improved sensitivity and possibly being able to discriminate between different physical parameters.

ACKNOWLEDGEMENTS

This work was supported by "Project "NanoSTIMA: Macro-to-Nano Human Sensing: Towards Integrated Multimodal Health Monitoring and Analytics/NORTE-01-0145-FEDER-000016" is financed by the North Portugal Regional Operational Programme (NORTE 2020), under the PORTUGAL 2020 Partnership Agreement, and through the European Regional Development Fund (ERDF).

REFERENCES

Brambilla, G. *et al.*, 2009. Optical fiber nanowires and microwires: fabrication and applications. *Advances in Optics and Photonics*, 1, pp.107–161.

Chen, G. and Ding, M., 2013. A review of microfiber and nanofiber based optical sensors. *The Open Opt. J*, 7(1), pp.32–57.

Chen, Z. *et al.*, 2011. Optically tunable microfiber-knot resonator. *Optics Express*, 19(15), p.14217.

De Freitas, J.M., Birks, T.A. and Rollings, M., 2015. Optical micro-knot resonator hydrophone. *Optics Express*, 23(5), pp.5850–5860.

Gomes, A.D. and Frazão, O., 2016. Mach – Zehnder Based on Large Knot Fiber Resonator for Refractive Index Measurement. *IEEE Photonics Technology Letters*, 28(12), pp.1279–1281.

Gouveia, M.A. *et al.*, 2014. Analysis of immersed silica optical microfiber knot resonator and its application as a moisture sensor. *Appl. Opt.*, 53(31), pp.7454–7461.

Hübert, T. *et al*., 2011. Hydrogen sensors - A review. *Sensors and Actuators, B: Chemical*, 157(2), pp.329–352.

Jiang, X., Yang, Q., *et al*., 2006. Demonstration of microfiber knot laser. *Applied Physics Letters*, 89(14), pp.2004–2007.

Jiang, X., Tong, L., *et al*., 2006. Demonstration of optical microfiber knot resonators. *Applied Physics Letters*, 88(22), pp.2004–2007.

Jiang, X.D. *et al.*, 2007. All-fiber add-drop filters based on microfiber knot resonators. *Optics Letters*, 32(12), pp.1710–1712.

Li, X. and Ding, H., 2014. A Stable Evanescent Field-Based Microfiber Knot Resonator Refractive Index Sensor. *IEEE Photonics Technology Letters*, 26(16), pp.1625–1628.

Liao, Y. *et al*., 2015. Salinity sensing based on microfiber knot resonator. *Sensors and Actuators A: Physical*, 233, pp.22–25.

Liao, Y. *et al*., 2016. Simultaneous Measurement of Seawater Temperature and Salinity Based on Microfiber MZ Interferometer with a Knot Resonator. *IEEE Journal of Lightwave Technology*, 34(23), pp.5378–5384.

Lim, K.-S. *et al*., 2012. Integrated microfibre device for refractive index and temperature sensing. *Sensors*, 12(9), pp.11782–11789.

Lou, J., Wang, Y. and Tong, L., 2014. Microfiber optical sensors: A review. *Sensors*, 14(4), pp.5823–5844.

Silva, S.F. *et al*., 2012. A review of palladium-based fiber-optic sensors for molecular hydrogen detection. *IEEE Sensors Journal*, 12(1), pp.93–102.

Vienne, G. *et al*., 2009. Demonstration of a reef knot microfiber resonator. *Optics express*, 17(8), pp.6224–6229.

Vienne, G., Li, Y. and Tong, L., 2007. Effect of host polymer on microfiber resonator. *IEEE Photonics Technology Letters*, 19(18), pp.1386–1388.

Wadell, C., Syrenova, S. and Langhammer, C., 2014. Plasmonic Hydrogen Sensing with Nanostructured Metal Hydrides. *ACS Nano*, 8(12), pp.11925–11940.

Wu, X., Gu, F. and Zeng, H., 2015. Palladium-Coated Silica Microfiber Knots for Enhanced Hydrogen Sensing. *IEEE Photonics Technology Letters*, 27(11), pp.1228–1231.

Wu, Y. *et al.*, 2012. Microscopic multi-point temperature sensing based on microfiber double-knot resonators. *Optics Communications*, 285(8), pp.2218–2222.

Wu, Y., Rao, Y.-J., *et al*., 2009. Miniature fiber-optic temperature sensors based on silica/polymer microfiber knot resonators. *Optics Express*, 17(20), pp.18142–18147.

Wu, Y. *et al*., 2011. Miniature interferometric humidity sensors based on silica/polymer microfiber knot resonators. *Sensors and Actuators, B: Chemical*, 155(1), pp.258–263.

Wu, Y., Zeng, X., *et al*., 2009. MOEMS accelerometer based on microfiber knot resonator. *IEEE Photonics Technology Letters*, 21(20), pp.1547–1549.

Xiao, L. and Birks, T. A, 2011. High finesse microfiber knot resonators made from double-ended tapered fibers. *Optics letters*, 36(7), pp.1098–1100.

Xu, Y. *et al*., 2014. A simple, polymer-microfiber-assisted approach to fabricating the silica microfiber knot resonator. *Optics Communications*, 321, pp.157–161.

Xu, Y. *et al*., 2015. Enhanced slow light in microfiber double-knot resonator with a Sagnac loop reflector. *Optics Communications*, 350, pp.148–153.

Xu, Y. *et al.*, 2015. Wideband slow light in microfiber double-knot resonator with a parallel structure. *Journal of Applied Physics*, 118(7), p.73105.

Xu, Z. *et al*., 2015. Highly sensitive refractive index sensor based on two cascaded microfiber knots with vernier effect. *Optics express*, 23(5), pp.6662–6672.

Yang, H. *et al*., 2014. Temperature sensing in seawater based on microfiber knot resonator. *Sensors*, 14(10), pp.18515–18525.

Yu, C.-B. *et al*., 2016. Graphene oxide deposited microfiber knot resonator for gas sensing. *Optical Materials Express*, 6(3), pp.727–733.

Yu, H. *et al*., 2014. Solution concentration and refractive index sensing based on polymer microfiber knot resonator. *Applied Physics Express*, 7(2), pp.3–7.

Zeng, X. *et al.*, 2009. A temperature sensor based on optical microfiber knot resonator. *Optics Communications*, 282(18), pp.3817–3819.