Development of a ring cavity-based fibre optic sensor for MR-compatible medical sensing applications.

BHAVSAR, K., VISWAMBARAN, V., JOHNY, J., KAILASNATH, M., MELZER, A. and PRABHU, R.

2019

IOP Conference Series: Materials Science and Engineering

Development of a ring cavity-based fibre optic sensor for MR-compatible medical sensing applications

IOP Conf. Series: Materials Science and Engineering **499** (2019) 012013 doi:10.1088/1757-899X/499/1/012013

Development of a ring cavity-based fibre optic sensor for MR-compatible medical sensing applications

K Bhavsar[1], V Viswambaran[1], J Johny[1], M Kailasnath[3], A Melzer[2] and R Prabhu[1]

[1]School of Engineering, Robert Gordon University, Aberdeen, UK
[2]Institute for Medical Science and Technology, University of Dundee, Dundee, UK
[3]International School of Photonics, Cochin University of Science & Technology, Kochi, India

Email: k.bhavsar@rgu.ac.uk

Abstract. Advances in robotic systems and rapid developments in minimally invasive surgery (MIS) have made their use possible in the operating room due to many distinct advantages offered by MIS over conventional surgical procedures. The constant increase of medical examinations, surgeries and surgical interventions using intraoperative guidance with magnetic resonance imaging (MRI) has promoted research on new sensors to be applied in this scenario. However, due to the challenging environment under MRI system limits the applicability of materials and traditional electronic sensors. Optical fibres are small in size, chemically inert, immune to electromagnetic interference and offer the real-time *in vivo* multi-parameter measurement capability. Herein, we report a ring cavity-based fibre optic sensor design using MR-compatible polymer material. Optical fibres were used to excite surface resonance modes (SRM) of the ring cavity-based sensor. The paper reports initial investigations on ring cavity based MR-compatible fibre optic sensor design. Computational simulations were carried out to study the effect of structural and material parameters on the sensor design. Ring cavity was developed using polymethyl methacrylate. Developed ring cavity will be used to develop the MR-compatible fibre optic sensor for medical applications.

1. Introduction

Growing interest in minimally invasive surgery (MIS) and rapid technological developments in medical robotics have made their use possible in the operating room [1]. MIS offers several distinct advantages over conventional operations such as reduction in pain experienced by the patient, less recovery time, tissue trauma and scars and reduced risk of post-operative infection. MIS is performed through small incisions with specialized equipments and under the guidance of imaging modalities such as magnetic resonance imaging (MRI). MRI examinations present a challenging environment involving a strong magnetic field and radiofrequency pulses. A basic component of MRI system is the static magnetic field which is about 100 000 times stronger than the earth's magnetic field [2]. Besides this strong magnetic field, MRI systems require a very homogeneous magnetic field within the field of view. Presence of materials which are not MRI compatible can experience deflection force or torque under the strong magnetic field or may experience heating effect, or eddy currents may be induced due to time-varying magnetic field [3]. Therefore, traditional electronic sensors cannot be used in such an environment.

Optical fibres offer several advantages such as chemical inertness, no electromagnetic interference (ideal for MR compatibility), small size allows miniaturization adequate for most common MIS medical applications and support integration of micro-/nanosensors on the fibre tip and has the capability to monitor multi-parameters in real-time *in vivo* [4-6]. Optical fibres can be used to excite surface resonance modes (SRM) of a ring cavity design [7]. Specific SRM can be created around the ring cavity which is highly sensitive to the surrounding environmental conditions in nano to micrometer distances from the surface. These resonant surface waves highly depend on the ring cavity design [8]. The phenomena of SRM of the ring cavity was utilised to develop the fibre optic sensor. Herein, we present the design and development of a ring cavity-based MR-compatible fibre optic sensor for medical applications. The paper reports initial investigations on sensor design parameters and development of ring cavity sensor using MR-compatible polymer material. Developed ring cavity-based fibre optic sensor will be used to measure physiological conditions for MR-guided MIS applications.

2. Theory

A simplest design of a ring-cavity resonator consists of a straight waveguide and a ring waveguide. A light guided through an input port, partially couples to the ring-cavity waveguide when placed close to each other. A resonance occurs when the optical path length of the ring-cavity resonator is exactly a whole number of wavelengths. Figure 1 shows the schematic diagram of the typical ring cavity resonator.

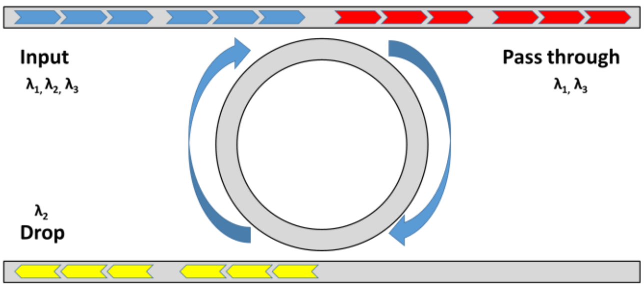

Figure 1. A schematic diagram of a ring cavity resonator.

If the wavelength, for example, λ_i satisfies the resonant condition, that is,

$$n_{eff}L = m\lambda_i \tag{1}$$

the coupling of the wave with wavelength λ_i will be enhanced and all others will be suppressed. As a result, only λ_i will be dropped from passing through the waveguide, while the rest of the wavelengths will pass through. Here n_{eff} is the effective index of the bending waveguide, L is the length of the ring, and m is an integer. Light propagates through total internal reflection inside the ring cavity along the curved boundary and forms a resonant optical mode. The resonant wavelength, λ, is given by [7]:

$$\lambda = \frac{2\pi r n_{eff}}{m} \tag{2}$$

where r is the radius of the ring resonator, n_{eff} is the effective refractive index of the propagating optical resonant mode, and m is an integer. The coupled light circulates the ring cavity surface and interacts with the surrounding medium through an evanescent field. As compared to straight waveguide-based sensors, the effective light-analyte interaction length of a ring cavity sensor is given by the number of revolution of light supported by the ring cavity resonator and is determined by [7]:

$$L_{eff} = \frac{Q\lambda}{2\pi n} \tag{3}$$

where Q is the quality factor (Q-factor), which represents the number of round trips that circulating light makes along the ring cavity resonator and n is the refractive index of the resonator. The Q-factor usually ranges from 10^4 to 10^8 depending on its configuration and hence despite their small physical size, it gives few tens of centimetres effective interaction length [7]. The quality (Q) factor, defined as the ratio of resonance wavelength to full width at half maximum (FWHM), is one of the fundamental parameters for ring-cavity resonators. Resonators with high Q factors are highly desirable for high-sensitivity sensors. The Q-factor is defined as,

$$Q = \frac{\lambda}{\delta\lambda} \tag{4}$$

where resonance wavelength λ shifts with the change in geometry, material properties (i.e. refractive index) and the surrounding environment. This phenomenon is being utilised for the ring cavity-based sensor development.

3. Results and discussions

Computational investigations were carried out on design parameters of the ring cavity-based fibre optic sensor. COMSOL Multiphysics 5.1 was used to study the computational results of different design parameters of ring cavity sensor design. The initial study was carried out using commonly used materials for ring cavity design i.e. silica and silicon nitride and the results will be exploited further for the sensor design using polymer materials. Analysis of different geometrical and material parameters i.e. ring cavity core thickness and refractive index were carried out. Refractive index of the core and cladding were 1.44 and 2.46 respectively. The width of the core and cladding were 0.2 and 2 μm respectively. Figure 2(a) shows the image of the ring cavity structure showing the E-field distribution along the waveguide. Figures 2(b) shows the resonance wavelength (i.e. 1556 nm) in the transmission spectrum of the waveguide.

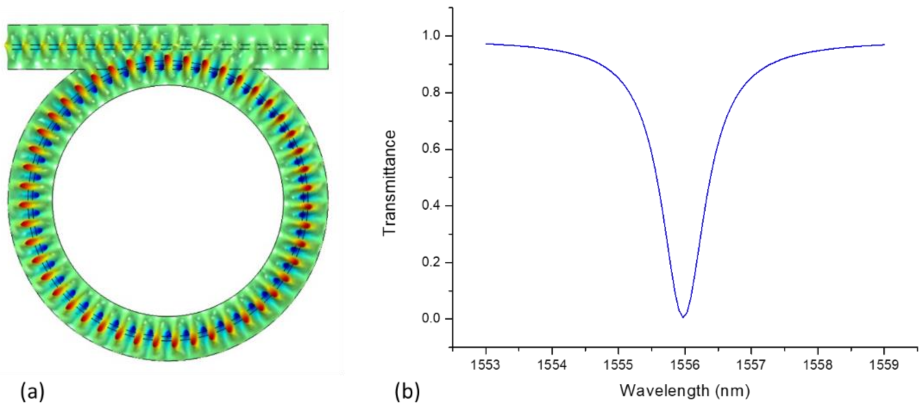

Figure 2. shows the (a) E-field distribution in the ring cavity sensor design and (b) transmission spectrum through the ring cavity sensor.

Effects of material property, such as refractive index and geometrical design parameter such as the width of the core on the resonance wavelength of the ring cavity sensor were studied. Figure 3(a) and

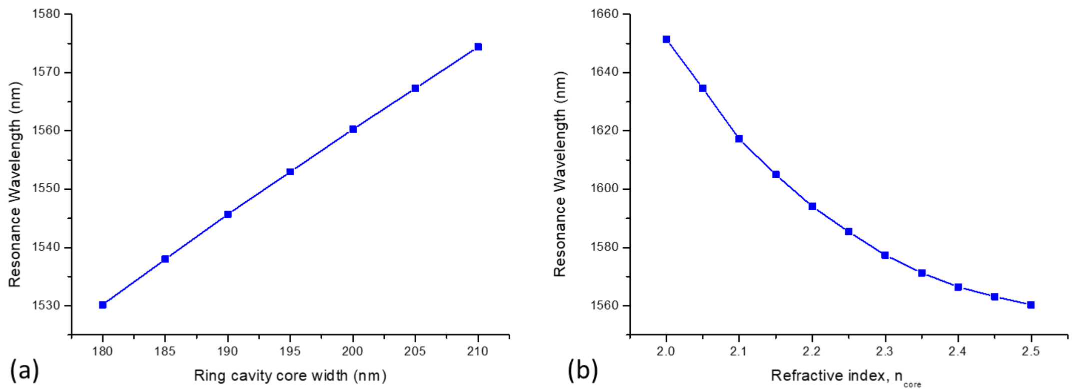

Figure 3. shows the effect on the resonance wavelength of the ring cavity with (a) core width and (b) refractive index.

(b) shows the resonance wavelength spectrum with core width and refractive index variation respectively. It was observed that the resonance wavelength of the ring cavity increases with the core width and decreases with refractive index. The observed shift can be attributed to the change in effective refractive index of the propagating optical mode.

4. Ring cavity-based sensor development

Susceptibility of the polymer materials such as polymethyl methacrylate (PMMA), polyetheretherketone (PEEK), polyimide and polydimethylsiloxane (PDMS) is close to the water and hence can be used safely under the strong magnetic field of MRI system [9]. PMMA has good optical transparency and has been used as a waveguide and optical device fabrication platform for many optical applications [10,11]. Many fluorescent dyes and rare earth ions have been used as dopants in the PMMA for various applications. Therefore, PMMA has been used as a primary test material to develop the ring cavity resonator. The ring cavity was developed using a PMMA as shown in figure 4.

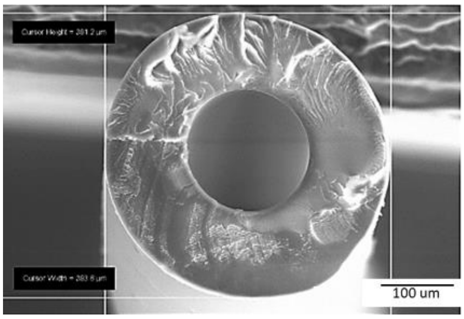

Figure 4. Scanning electron microscopic image of the ring cavity.

Figure 5 (a) shows the schematic representation of the ring cavity-based sensor for the measurement of physiological conditions. Change in temperature, pressure or refractive index inside the ring cavity modifies the n_{eff} of the guiding resonant mode, which in turn leads to a shift in the spectral position, as illustrated in Figure 5(b). Thus, by directly or indirectly monitoring the resonant spectral shift, kinetic and quantitative information about the change in physiological conditions near the surface can be assessed [7]. Specificity to the varying parameter can be achieved by coating the ring cavity with specific molecules responding to selective parameters.

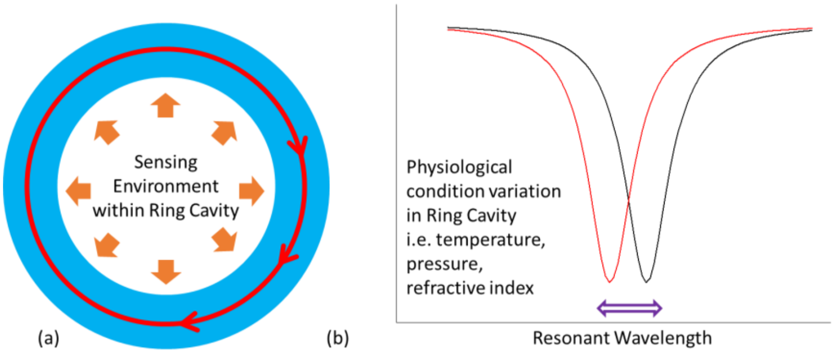

Figure 5 (a) A schematic design of an optical ring cavity-based MR-compatible fibre optic sensor and (b) shift in resonance wavelength in response to variation in physiological conditions.

5. Conclusion

Design and development of a ring cavity-based MR-compatible fibre optic sensor was carried out. Effects of ring cavity material property and geometry variation on the sensor design were studied. Ring cavity was developed using PMMA. Developed ring cavity-based MR-compatible fibre optic sensor will be used to measure physiological conditions during MR-guided MIS applications.

Acknowledgement
The authors would like to thank the EPSRC Image-Guided Therapies Network Plus for funding the work.

References

[1] Puangmali P, Althoefer K, Seneviratne LD, Murphy D and Dasgupta P. (2008) State-of-the-art in force and tactile sensing for minimally invasive surgery. *IEEE Sensors Journal,* **8**, 371-81.
[2] Duppenbecker PM, Weissler B, Gebhardt P, Schug D, Wehner J, Marsden PK, et al. (2016) Development of an MRI-compatible digital SiPM detector stack for simultaneous PET/MRI. *Biomedical Physics & Engineering Express,* **2**, 015010.
[3] Schueler B, Parrish T, Lin J, Hammer B, Pangrle B, Ritenour E, et al. (1999) MRI compatibility and visibility assessment of implantable medical devices. *Journal of Magnetic Resonance Imaging,* **9**, 596-603.
[4] Taffoni F, Formica D, Saccomandi P, Di Pino G and Schena E. (2013) Optical Fiber-Based MR-Compatible Sensors for Medical Applications: An Overview. *Sensors,* **13**, 14105-20.
[5] Bhavsar K, Prabhu R and Pollard P. (2013) Development of dithizone based fibre optic evanescent wave sensor for heavy metal ion detection in aqueous environments. *Journal of Physics: Conference Series,* **450**, 012011.
[6] Mathews CB, Libish TM, Bhavsar K, Vivek V, Prabhu R and Radhakrishnan P. (2016) A fiber optic biosensor for the detection of cholesterol levels based on chitosan coated long period grating. *Optoelectronics Letters,* **12**, 23-6.
[7] Sun Y and Fan X. (2011) Optical ring resonators for biochemical and chemical sensing. *Analytical and Bioanalytical Chemistry,* **399**, 205-11.
[8] Sun Y and Fan X. (2008) Analysis of ring resonators for chemical vapor sensor development. *Optics Express,* **16**, 10254-68.
[9] Wapler MC, Leupold J, Dragonu J, von Elverfeld D, Zaitsev M and Wallrabe U. (2014) Magnetic properties of materials for MR engineering, micro-MR and beyond. *Journal of Magnetic Resonance,* **242**, 233-42.
[10] Zhao Y, Wang F, Cui Z, Zheng J, Zhang H, Zhang D, et al. (2004) Study of reactive ion etching process to fabricate the PMMA-based polymer waveguide. *Microelectronics Journal,* **35**, 605-8.
[11] Koo J, Williams R, Gawith C, Watts S, Emmerson G, Albanis V, et al. (2003) UV written waveguide devices using crosslinkable PMMA-based copolymers. *Electronics Letters,* **39**, 394-5.