Chapter 2
Tunable Lasers Based on Multimode Interference Effects

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Abstract We review the development of multimode interference (MMI) based wavelength tunable fiber lasers. The key advantages of MMI devices as tunable filters are its band-pass spectral response and the simplicity in their fabrication. Different approaches are reviewed in an effort to achieve wide tuning ranges. The maximum tuning range is close to 90 nm and a side-mode suppression ratio (SMSR) better than 50 dB is demonstrated with a single MMI filter. The wide tuning range demonstrates the potential of MMI devices for tunable laser applications.

2.1 Introduction

Fiber laser systems have received a great deal of interest due to their significant advantages as compared to their bulk counterparts. Due to their all-fiber configuration, inclusion into tunable fiber lasers is straight-forward and result in very stable, compact and robust laser systems. These lasers can also achieve very high output powers over a wide span of lasing wavelengths due to the availability of a variety of different gain media. Another feature that makes fiber lasers highly attractive for telecommunications and sensing applications is the ability to tune the lasing wavelength over a broad range. Over the years many different techniques have been proposed and demonstrated such as bulk gratings [1], fiber Bragg gratings [2–4], Mach-Zehnder interferometer [5], and Fabry Perot cavities [6–8]. The main issues with such techniques are that they are either expensive due to the fabrication process or require complex setups in which alignment issues could make the laser highly sensitive to environmental conditions.

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A device that is based on multimode interference (MMI) effects, has lately been successfully employed as a tunable filter for fiber laser applications. The main features of a MMI device are that it exhibits a band-pass spectral response with minimal transmission loss at the peak of the band and its fabrication is very simple. In fact since a MMI is fabricated by basically splicing a section of multimode fiber (MMF) between two single mode fibers (SMF), we do not require expensive or elaborate fabrication processes. This chapter provides an overview of the different techniques that have been used to achieve wavelength tunable lasers based on MMI effects.

2.2 Multimode Interference in Optical Fibers

The development of photonic devices based on multimode interference (MMI) effects was initially fueled by applications in the field of integrated optics [9–11]. This was mainly related to the great flexibility on the design of multimode waveguides (MMW) of almost any size and shape, input and output waveguides at any desired position, as well as active control via electro-optic and thermo-optic effects [12–14]. Since the only requirement to observe MMI effects is to have a MMW, a variety of applications have been recently developed using MMI effects in MMF such as sensors for different applications [15–19]. Here we provide an overview of the basic concepts behind the self-imaging process in MMI devices, as well as its potential application as a tunable filter for the development of tunable lasers.

2.2.1 Multimode Interference Effect

The key requirement in order to observe MMI effects in optical fibers is to use a MMF that is designed to support several modes (typically ≥ 3). This can be easily achieved in optical fibers using either commercial or specialty MMF. When light is coupled into the MMF, the modes that are supported by the MMF are excited and the interference between the propagating modes gives rise to an interference pattern along the MMF. At certain positions light is concentrated along the central axis of the MMF forming replicas of the input field known as self-images. The formation of such self-images can be better observed by using the commercial beam propagation software BeamPROP from the company RSoft. Here light propagates in a short segment of SMF that is spliced to another section of MMF. The parameters used in the simulations consists of a standard SMF (SMF-28) with a core diameter of 9 μm, and core and cladding refractive index (RI) of 1.4504 and 1.4447 at 1550 nm, respectively. The MMF is a special fiber known as No-Core fiber, which is a solid optical fiber with air effectively as its cladding. The No-Core MMF has a diameter of 125 μm and a RI of 1.4440 at 1550 nm. As shown in Fig. 2.1, after the light with a wavelength of 1550 nm is coupled into the No-Core MMF, we can observe the interference pattern as well as four positions (marked by arrows) where optical

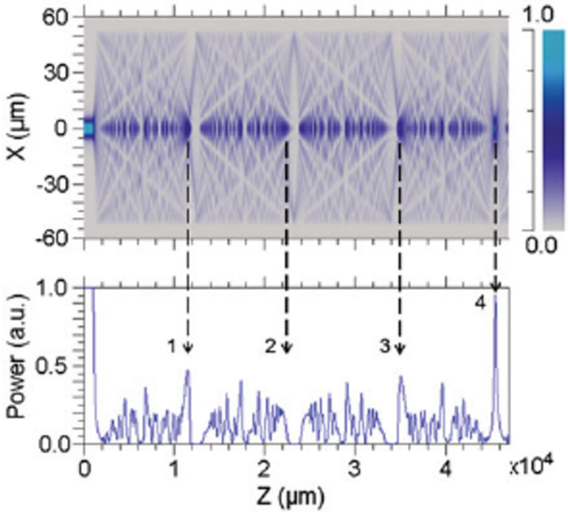

Fig. 2.1 Light propagation in a MMI fiber device at 1550 nm. The arrows correspond to positions where images are formed

intensity is concentrated. By monitoring the transmitted intensity along the No-Core MMF axis with an area similar to that of the SMF, we can observe the quality of the images formed where the light is concentrated. The images labeled from one to three are known as pseudo-images. These images are formed due to the symmetric light coupling into the No-Core MMF and they exhibit more attenuation. The fourth image corresponds to the real self-image which exhibits significantly higher intensity as compared to the pseudo-images. Based on Fig. 2.1 it is clear that, if we manage to cleave the MMF exactly at the position where the self-image is formed and we splice a SMF, the light will be coupled to this output SMF with very low losses. Therefore, light at 1550 nm will be transmitted through this SMF-MMF-SMF device with negligible losses due to MMI effects.

2.2.2 *Self-Imaging Properties*

When light is coupled to a MMF that supports several modes, it is important to highlight that the number of excited modes is related to the transversal position where the light is coupled into the MMF. This has direct impact on the length at which the self-images are formed, as well as the number of self-images that are formed for a particular length. Typically, when a SMF fiber is spliced to a MMF using standard splicing procedures, the fundamental mode is coupled exactly at the center of the MMF. Under this condition light coupled in the MMF will be coupled preferentially to the modes that possess radial symmetry and only the LP_{0m} modes are excited in the MMF [20]. Due to the circular symmetry of the fundamental mode of the SMF, the input light can be assumed to have a field distribution of $\psi(r,\phi,0)$, i.e. radial symmetry at $z = 0$. When the light is launched into the MMF, the input field can be decomposed into the guided modes of the MMF as follows,

$$\psi(r,\varphi,0)=\sum_{\nu=1}^{m}c_\nu\phi_\nu(r,\varphi,0), \tag{2.1}$$

where m is the number of guided modes, $\phi_\nu(r,\varphi,0)$ is the electric field of the νth guided mode of the MMF, and c_ν is the mode expansion coefficient which can be determined using the overlap integral,

$$c_\nu=\frac{\iint\psi(r,\varphi)\phi_\nu(r,\varphi)ds}{\iint|\phi_\nu(r,\varphi)|^2ds} \tag{2.2}$$

If we neglect mode conversion, we can assume that all the excited modes propagate independently inside the MMF. Therefore, we can obtain the field after propagating a distance z by

$$\begin{aligned}\psi(r,\varphi,z)&=\sum_{\nu=1}^{m}c_\nu\phi_\nu(r,0)\,e^{-i\beta_\nu z}\\&=e^{-i\beta_1 z}\sum_{\nu=1}^{m}c_\nu\phi_\nu(r,0)\,e^{-i(\beta_\nu-\beta_1)z}\end{aligned} \tag{2.3}$$

where β_1 and β_ν are the propagation constants of the fundamental and the ν^{th} guided mode in the MMF. We can observe from Eq. (2.3) that if the phase factor $(\beta_\nu-\beta_1)z$ is an exact multiple of 2π we obtain an exact replica of the input field. This distance corresponds, as we explained before, to the position where the self-image is formed.

An analytical solution can be obtained under the asymptotic formulation [21] by expressing the difference in the longitudinal propagation constants between two radial modes as a function of the MMF parameters (core RI and diameter) and the operating wavelength [22]. Therefore, by expressing the operating wavelength as a function of all other terms, the following expression is obtained,

$$\lambda_0=p\frac{n_{MMF}D_{MMF}^2}{L_{MMF}}\quad with\quad p=0,1,2,\ldots, \tag{2.4}$$

where λ_0 is the free space wavelength, L_{MMF} is the length of the MMF, n_{MMF} and D_{MMF} are respectively the effective RI and diameter of the fundamental mode. The factor p denotes the periodic nature of the imaging process along the MMF. Therefore, at every fourth image ($p=4$, 8, 12, ...) we obtain the real self-image, and this is typically the position that we use for tuning applications. Other images obtained for any other value of p correspond to the pseudo-images. We can observe from Eq. (2.4) that the transmitted wavelength is inversely proportional to the MMF length. Therefore, we can control at will this wavelength by just changing the length of the MMF. We should also notice that the MMI response to variations in length is highly linear, which is good for tuning applications.

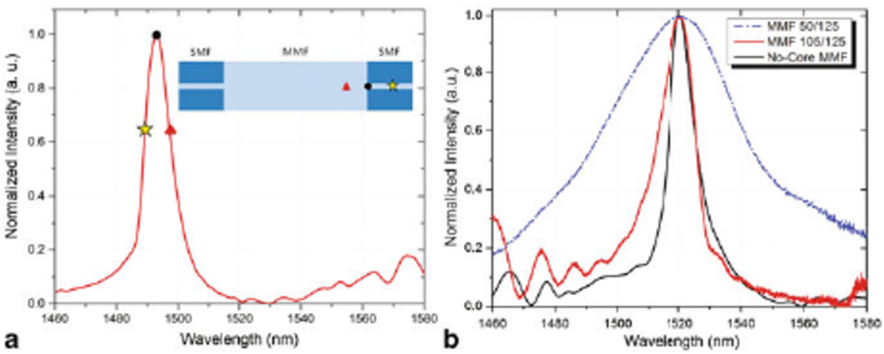

Fig. 2.2 **a** Spectral response of a MMI device (inset: self-image position along the MMF for different wavelengths) and **b** Spectral response of MMI devices with different MMF diameters

2.2.3 Spectral Response of MMI Devices

So far, we know that in a MMI device there is a particular wavelength that will be transmitted with very low attenuation, and that wavelength can be selected by setting the particular length of the MMF section. However, the most interesting property of MMI devices is in their spectral responses. In order to obtain the transmitted MMI intensity as a function of wavelength we use a tunable laser with a spectral range spanning from 1460 to 1580 nm. The laser beam is coupled to the MMI device and its wavelength is scanned while maintaining a constant intensity, and the transmitted power is measured using a photo-detector. As shown in Fig. 2.2a, the response exhibits a band-pass filter response whose peak wavelength is exactly the design wavelength as dictated by Eq. (2.4).

The band-pass behavior of the MMI device can be explained as follows. As shown in the inset of Fig. 2.2a, the peak wavelength exhibits maximum transmission because the MMI was designed to operate at such wavelength, and the self-image is formed right at the output MMF-SMF interface (circle). Any other wavelength will form a self-image before (longer wavelength, triangle) or after (shorter wavelength, star) the MMF-SMF interface, which will significantly reduce the light coupled to the output SMF. The diameter of the MMF also plays a significant role on the bandwidth of the band-pass filter. As shown in Fig. 2.2b the bandwidth is reduced when the diameter of the MMF is increased. The only drawback in this case is that a longer MMF is needed to obtain the same peak transmission wavelength. Therefore, there is a trade-off between diameter and length of the MMF in order to fabricate a MMI device with an optimum length. The band-pass filter response of the MMI presents itself as being ideal for wavelength tuning of lasers if the wavelength of the MMI peak transmission can be tuned in real time.

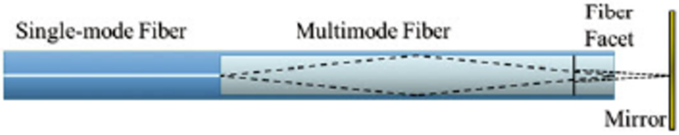

Fig. 2.3 Schematic of the free space wavelength tuning MMI device

2.3 Mechanically Tunable MMI Fiber Lasers

Based on Eq. (2.4), it is clear that in order to tune the MMI peak wavelength we have limited options. A straightforward approach is to attempt to increase or decrease in real time the length of the MMF. Since the peak wavelength is inversely proportional to the MMF length we should also obtain a linear response which is beneficial for developing tunable lasers.

2.3.1 Free Space Tunable Laser

In order to change the MMF length in real time the tuning mechanism of Fig. 2.3 was proposed [23]. The basic idea is to calculate the MMF length where the self-image will be formed for the operating wavelength using Eq. (2.4). Then, we cleave the MMF at a length slightly shorter than the self-image distance. Therefore, the light exiting the MMF will converge to a point beyond the fiber facet (in air) and forms a beam waist with a plane wavefront. If a mirror is placed at this free-space location where this self-image point occurs, the light will be reflected back into the MMF and the operating wavelength will be coupled back to the input SMF fiber. Since the self-image position is wavelength dependent, by changing the position of the mirror along the MMF axis we can control the MMI peak transmission wavelength. Therefore, this effect can be used to select a specific wavelength from a broad spectrum by simple changing the position of the mirror. A broadband mirror is needed to operate the device over a wide wavelength range.

Using a beam propagation method the first pseudo-image is found to be formed at a distance of 15.2 mm for a standard 105/125 MMF at a wavelength of 1080 nm. In the experiments, the MMF was then cleaved at 15 mm. The tuning mechanism was used to fabricate a wavelength tunable double-clad fiber laser. As shown in Fig. 2.4 it consists of a double-clad Ytterbium-doped fiber (DCYDF) with a core/cladding diameter of 6/125 μm and a 0.14/0.45 numerical aperture [24]. The length of the DCYDF was 16 m, which corresponds to 7.2 dB of pump absorption (only $\sim$80 % of the pump light is absorbed by the active core). The DCYDF is end-pumped by a fiber pig-tailed multi-mode laser diode with 3 W of fiber-coupled output power at a wavelength of 915 nm. As can be seen in Fig. 2.4, the pump light was launched into the DCYDF via a focusing lens that has a broadband anti-reflection coating covering the pump wavelength. The end of the DCYDF used for pumping was cleaved to

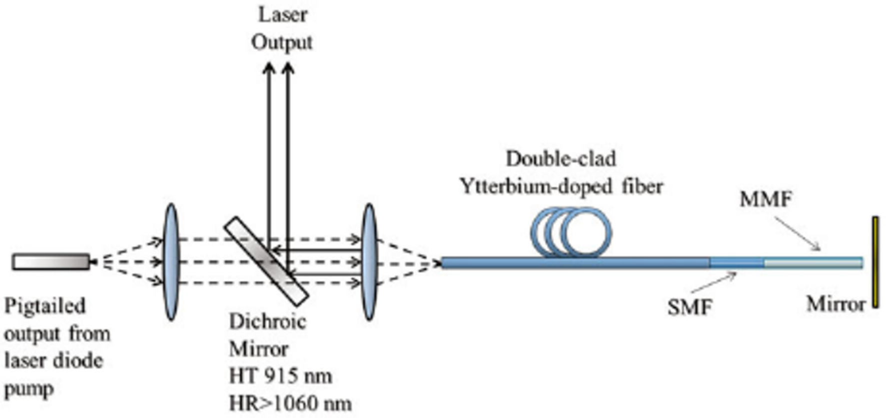

Fig. 2.4 Schematic of Ytterbium doped tunable fiber laser

provide feedback for laser oscillation, and also to operate as the output coupler for the laser. The other end of the fiber was spliced to the SMF of the tuning mechanism. A dichroic mirror placed between the fiber pigtailed laser and the DCYDF is used to separate the laser output from the path of the pump beam.

As shown in Fig. 2.5, as the mirror is moved away from the MMF the laser emission is tuned to shorter wavelengths. A total tuning range of 8 nm and average output power of 500 mW is achieved. The main limitation of the tuning mechanism to obtain a wider tuning range is related to the alignment of the MMF facet with the mirror. If the MMI facet and the mirror are not perfectly parallel to each other, the propagation losses increase very rapidly and maintaining optimal alignment becomes increasingly difficult as their separation is increased. Nevertheless, this is an excellent proof of principle to demonstrate the feasibility of using a MMI filter to achieve wavelength tunable fiber lasers.

2.3.2 *Ferrule Based Tunable Laser*

A simple way to significantly reduce the free space alignment issues highlighted in the previous section is by using the tunable MMI filter configuration as shown in Fig. 2.6 [25]. In this setup the ferrule is filled with an index matching liquid whose RI is higher than that of the ferrule material but lower than that of the No-Core MMF. In this way, a liquid MMF (LMMF) is created inside the ferrule while the liquid RI is low enough and does not alter the waveguide properties of the No-Core MMF. Therefore, any gap between the SMF and MMF is now a LMMF, and this effectively increases the length of the MMF. By changing the separation between the SMF and MMF, we control the effective MMF length and thus wavelength tuning should be achieved. Given the tight tolerances of the ferrule and No-Core fiber dimensions, the

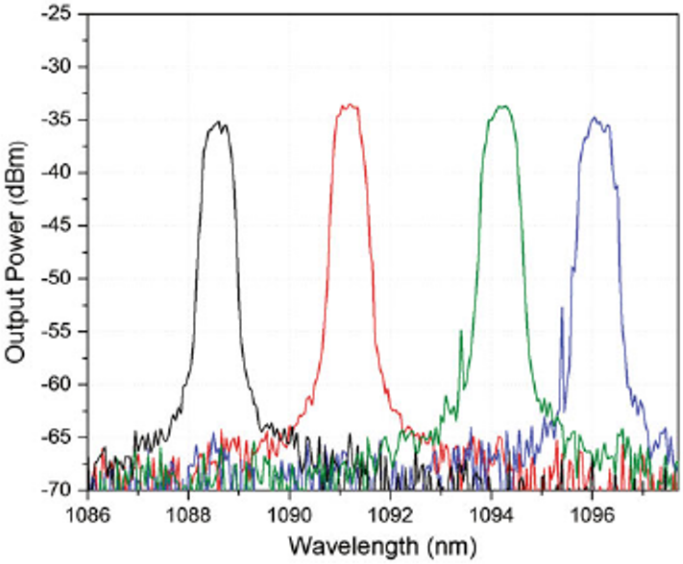

Fig. 2.5 Wavelength tuning characteristics of the double-clad Yb-doped fiber laser using the free space MMI tuning mechanism

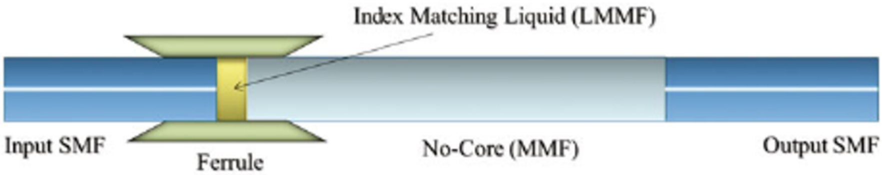

Fig. 2.6 Schematic of the ferrule based wavelength tuning MMI device

fibers are reasonably aligned in the transverse direction after their insertion into the ferrule. This also allowed us to move the fibers very smoothly along the propagation direction in order to tune the MMI filter.

The length of the fused silica ferrule (Polymicro Technologies) is 15 mm, with inner and outer diameters of 127 μm and 1700 μm respectively. The ends of the ferrule are flared to facilitate fiber insertion into the ferrule. The length of the No-Core fiber was 56 mm, which corresponds to a peak wavelength of 1611 nm, and the index controlled liquid RI was 1.442 (Cargille®). The tuning mechanism was characterized by first measuring the transmitted spectrum when the fibers inside the ferrule are in contact. The fibers are then separated in steps of 100 μm and the spectrum is acquired at each step. The MMI peak wavelength as a function of the separation of the fibers is shown in Fig. 2.7. A tuning range of 60 nm can be achieved with excellent linearity throughout the whole tuning range.

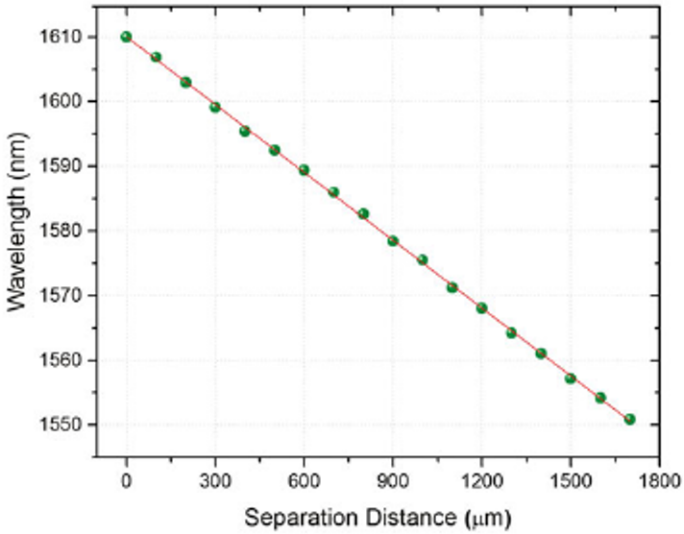

Fig. 2.7 Peak wavelength tuning range of the ferrule based tuning mechanism

The tuning mechanism was incorporated in an erbium-doped fiber laser (EDFL) with a standard ring cavity configuration, as shown in Fig. 2.8. The ring cavity is pumped by a 980 nm laser diode with 150 mW of maximum output power, which is coupled into the cavity using a 980/1550 wavelength division multiplexer (WDM). The WDM (port 3) was fusion-spliced with a 2.85 m long L-band Erbium-doped fiber (EDF) having a 0.25 NA and a concentration of 3000 ppm. The other cleaved end of the EDF was placed into the ferrule filled with liquid and works now as the input SMF into the MMI filter. The No-Core fiber spliced to the output SMF is inserted into the other end of the ferrule to complete the MMI filter. The output SMF in then spliced to a 10/90 coupler and the 90 % was spliced to an optical isolator to keep the ring cavity unidirectional. The ring cavity is closed by connecting the isolator output to the WDM (port 2). The 10 % output from the 10/90 coupler is used to monitor the laser output via an OSA. The laser was operated at the maximum pump power of 150 mW and the maximum laser output power was close to 1 mW. As shown in Fig. 2.8b the laser exhibits a total tuning range of 60 nm covering a wavelength range from 1549 nm to 1609 nm. The laser linewidth is close to 0.4 nm with a signal-to-noise (SNR) of 40 dB.

2.4 Optofluidically Tunable MMI Fiber Laser

An alternative way to tune the MMI peak transmission wavelength, as revealed in Eq. (2.4), is by modifying the effective RI and/or the diameter of the MMF. Heating the MMI device to achieve tuning via thermo-optics effects is not an option because

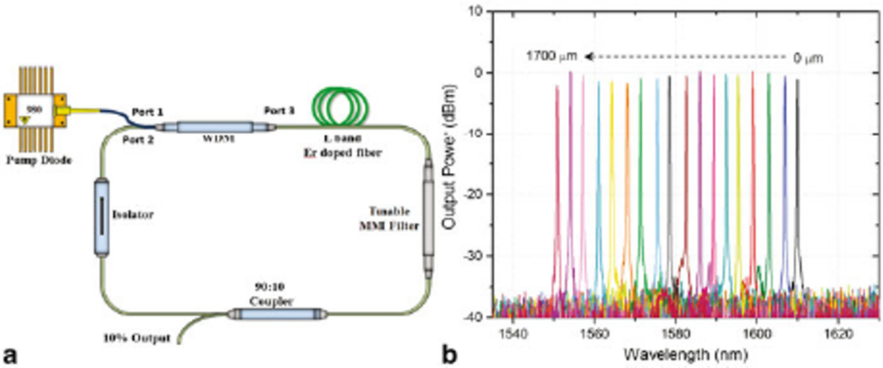

Fig. 2.8 **a** Schematic of the tunable ring cavity fiber laser based on MMI tunable filter and **b** Superimposed lasing spectra of the tunable laser with a total tuning range of 60 nm

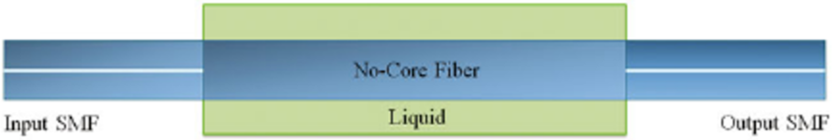

Fig. 2.9 Schematic of optofluidically tunable MMI filter

the thermo-optic effect in optical fibers is very small. In fact, MMI temperature sensors have been proposed and temperature sensitivities close to 15 pm/°C have been reported [26]. Such wavelength change as a function of temperature is too small to achieve a reasonable tuning range with small temperature increments. A simple way to change both effective RI and diameter is by using the No-Core fiber, and immersing it in liquids. Since the No-Core MMF has no cladding any changes to the liquid will alter the MMF parameters and thus the MMI peak wavelength.

2.4.1 *Optofluidic Tuning of MMI Filter*

The No-Core MMF becomes an ideal component if we want to modify the MMF parameters significantly. The fact that its core is completely exposed means that we can modify the MMF properties when the cladding region is modified. This is easily achieved by surrounding the No-Core fiber in liquids with different RI as shown in Fig. 2.9. When the index contrast between core and cladding is reduced, the effective RI and diameter of the No-Core fiber are increased and wavelength tuning of the MMI filter should be achieved [27].

Experimental demonstration of wavelength tuning is realized by splicing a 58.81 mm long No-Core MMF between two SMF, which corresponds to a MMI filter with a peak wavelength of 1534 nm. Liquids with different RI are obtained by

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