Laser Phys. **24** (2014) 085108 (6pp) doi:10.1088/1054-660X/24/8/085108

Wide range optofluidically tunable multimode interference fiber laser

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Received 29 April 2014, revised 16 May 2014
Accepted for publication 16 May 2014
Published 15 July 2014

Abstract

An optofluidically tunable fiber laser based on multimode interference (MMI) effects with a wide tuning range is proposed and demonstrated. The tunable mechanism is based on an MMI fiber filter fabricated using a special fiber known as no-core fiber, which is a multimode fiber (MMF) without cladding. Therefore, when the MMI filter is covered by liquid the optical properties of the no-core fiber are modified, which allow us to tune the peak wavelength response of the MMI filter. Rather than applying the liquid on the entire no-core fiber, we change the liquid level along the no-core fiber, which provides a highly linear tuning response. In addition, by selecting the adequate refractive index of the liquid we can also choose the tuning range. We demonstrate the versatility of the optofluidically tunable MMI filter by wavelength tuning two different gain media, erbium doped fiber and a semiconductor optical amplifier, achieving tuning ranges of 55 and 90 nm respectively. In both cases, we achieve side-mode suppression ratios (SMSR) better than 50 dBm with output power variations of less than 0.76 dBm over the whole tuning range.

Keywords: erbium-doped fiber laser, tunable laser, multimode interference, multimode fiber

(Some figures may appear in colour only in the online journal)

1. Introduction

Tunable fiber lasers are crucial components for a variety of photonic applications ranging from fiber sensors to telecommunication systems. In the case of sensing applications, tunable lasers are employed as elements for optical testing, analysis and metrology. Unlike single wavelength lasers, the versatility offered by tunable laser configurations relies on the ability to dynamically change both their spectral and intensity features [1]. Such characteristics make tunable lasers an ideal tool for the monitoring of multiplexed sensor systems. On the other hand, optical communication systems exhibit a never-ending demand for larger bandwidths, which increases considerably every year. Dense wavelength division multiplexing (DWDM) has been successfully used to increase the telecommunication bandwidth of single mode fibers (SMF) through using different carriers, i.e. different wavelengths, along a single optical fiber. In this respect, tunable lasers play a key role in the deployment of DWDM systems because they can easily replace the need for a set of lasers with specific wavelengths, which is a cost-effective approach for such systems [2, 3]. An important feature in the vast majority of tunable lasers is that their tuning range, and ultimately the cost of the laser, depends entirely on the technology employed to manufacture the tunable filters. Therefore, in order to reduce the cost of tunable lasers we need to develop a tunable filter that is inexpensive, while achieving a wide tunable range.

Based on their operational principle, and considering only widely tunable lasers with tuning ranges beyond 50 nm, there are nowadays a number of tunable lasers based on different technologies. Typical examples for wide wavelength tuning include Fabry–Perot cavities, bulk gratings, Mach–Zehnder interferometer filters, fiber Bragg gratings (FBG) and all-fiber Lyot filters, just to mention a few [4–15]. Several works have been previously reported based on Fabry–Perot cavities that exhibit very broad wavelength tuning ranges up to 100 nm [4, 5]. However, to achieve such a wide tuning range it is absolutely necessary to use two or more tunable Fabry–Perot filters, which is a great disadvantage because the tunable laser becomes a complex and expensive system. In the case of bulk grating filters [8], even when they exhibit a very fine bandpass wavelength response, their use eliminates the all-fiber laser arrangement and makes the system more sensitive to mechanical disturbances. A two-taper Mach–Zehnder interferometer filter has also been used to achieve wide wavelength tuning in the order of 55 nm [9]. However, very precise mechanical movements are required to bend one of the fiber tapers, which could be a drawback for the laser when operated continuously over long time periods. FBG [10–14] and all-fiber Lyot filters [15] have also been used but their tuning range is limited to below 50 nm. A device that has recently attracted a lot of attention for tunable laser applications is the one based on multimode interference (MMI) effects [16, 17]. The key features of MMI devices are related to their simple fabrication process, just splicing a multimode fiber (MMF) between two SMF, and the fact that they exhibit a bandpass filter response that can be used for tuning applications. Different MMI configurations have been used to tune MMI devices [18–20] but, so far, a maximum tuning range of 60 nm has been achieved [20]. Tuning was achieved by increasing the separation between an SMF and the MMF inside a liquid filled capillary tube, which effectively increases the length of the MMF. The main issue was related to the losses when the separation was too large, which ultimately limits the tuning range. In this work, we demonstrate a widely tunable all-fiber MMI fiber laser using an optofluidically tunable MMI filter. Wavelength tuning is achieved using an optofluidic mechanism in which a liquid moves vertically along the MMF and changes the optical properties of the fiber covered by the liquid. This is realized by using an MMF without cladding, also known as no-core fiber. Since the peak wavelength of MMI devices is directly related to the optical properties of MMF, wavelength tuning is achieved by moving the liquid along the no-core MMF. By using this MMI filter, a tunable ring cavity EDF laser was demonstrated covering a wavelength range of 55 nm, which was mainly limited by the available gain media. However, when the gain media are replaced by a broadband semiconductor optical amplifier (SOA), a tunability of almost 90 nm is achieved with excellent power uniformity. We should highlight that the device is quite simple and relatively inexpensive when compared with other tuning mechanisms.

2. Optofluidically tunable MMI fiber filter

The concept behind the operation of an MMI filter is quite simple and has been described elsewhere [17–20]. The key element is a segment of MMF, with a precise length, which is spliced between two SMF as shown in the inset of figure 1. The light launched into the MMF will excite the modes supported by the MMF, limited by the launching conditions, and as the modes propagate, they will form images of the input field along the MMF axis. Such images are formed when the accumulated phase difference between the modes is an integer multiple of 2π, such that the modes recombine in-phase. The MMI peak wavelength is governed by the following equation,

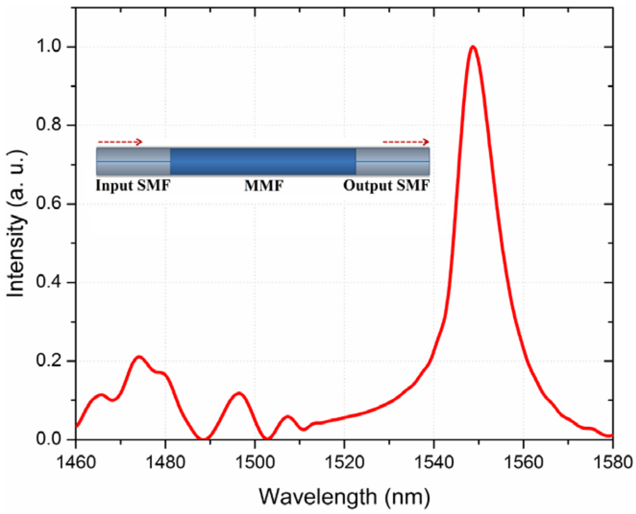

Figure 1. Spectral response of an MMI fiber filter (inset: schematic of an MMI fiber filter using no-core fiber).

$$\lambda_0 = \frac{4 n_{\mathrm{MMF}} D_{\mathrm{MMF}}^2}{L_{\mathrm{MMF}}}, \qquad (1)$$

where λ_0 is the free space wavelength, n_{MMF} and D_{MMF} correspond to the refractive index (RI) and diameter of the fundamental mode respectively, and L_{MMF} is the length of the MMF. As shown in equation (1), a specific MMF length corresponds to a particular peak wavelength that exhibits maximum transmission through the MMI filter. However, if we are detuned from this wavelength the image will be formed before or after the output MMF–SMF interface and coupling to the output SMF will be reduced. Therefore, when a continuum spectrum is sent through such an MMI device, a bandpass filter response is obtained as shown in figure 1.

Based on equation (1), a tunable MMI filter can be achieved by changing the parameters of the MMF, such as the RI of the MMF (thermo-optic effect) or the effective length of the MMF as described in [14]. A closer inspection of equation (1) reveals that a larger tuning effect could be obtained, because of its square dependence, if we were able to modify the diameter of the MMF in real time. Although this is not quite obvious to achieve, we can do this by employing a special MMF fiber known as a no-core fiber, which is basically an MMF without cladding. Therefore, when the fiber is immersed in a liquid with an RI value lower than that of the no-core fiber, the properties of the MMF will be modified. In fact, both n_{MMF} and D_{MMF} are modified, but if the RI of the liquid is close to that of the no-core fiber, the dominating

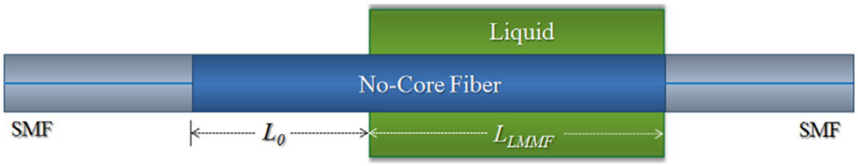

Figure 2. Schematic of the optofluidically tunable MMI fiber filter.

term will be the effective diameter. As shown in figure 2, rather than changing the RI around the entire no-core fiber length, we gradually increase or decrease the length of no-core fiber covered by the liquid. This is equivalent to having an MMI structure that is formed by two slightly different MMF. In this situation, the peak wavelength is calculated by adding the fractional phase contribution of each MMF segment. Therefore, the peak wavelength in such an MMI structure can be calculated by [21],

$$\lambda_0 = (4)\left[\frac{n_{\mathrm{LMMF}}D_{\mathrm{LMMF}}^2}{L_T}\left(\frac{L_{\mathrm{LMMF}}}{L_T}\right) + \frac{n_{\mathrm{MMF}}D_{\mathrm{MMF}}^2}{L_T}\left(\frac{L_0}{L_T}\right)\right] \quad (2)$$

where n_{LMMF} and D_{LMMF} correspond to the RI and diameter of the fundamental mode and L_{LMMF} is the length of the no-core fiber covered with liquid. Here, L_0 is the no-core fiber section without liquid and L_T is the total no-core fiber length. The variables in the second term of equation (2) are the same as described in equation (1) for the no-core fiber in air. As shown in equation (2), the advantage of our tunable MMI filter is that changes in the length of the no-core fiber, with and without liquid, provide a linear wavelength response while the slope is controlled by the effective RI and diameter, which is dictated by the RI of the liquid. Therefore, the largest tuning range should be obtained as the RI of the liquid approaches that of the no-core fiber because this provides maximum change of the effective RI and diameter.

The no-core fiber used in our experiments has an RI of n = 1.444 and diameter of 125 μm. In order to evaluate the tuning range of our design we fabricated MMI filters with no-core fiber lengths of 58.81, 59.91 and 61.28 mm, which correspond to peak wavelengths of 1534, 1506 and 1472 nm respectively. The liquids used for each MMI filter correspond to index matching liquids from Cargille® with RI values of 1.4050, 1.4340 and 1.4380 at 1550 nm, which are lower than the RI value of 1.444 of the no-core fiber. The MMI filter was interrogated using an Agilent tunable laser with a wavelength range from 1460 to 1580 nm, and the transmitted intensity was measured using a photodetector. The liquid level was raised in steps of 10 mm, and the spectrum was acquired at each step. As shown in figure 3(*a*), when the RI of the liquid is significantly lower (n = 1.4050) we observe that the spectrum is red-shifted as the liquid level increased, and a total tuning range of 37.4 nm is obtained. We can also notice that the signal intensity also increases, which we believe is related to the fact that scattering losses are reduced when the refractive index contrast is reduced. In the case of a liquid with an RI value that is very close to that of the no-core fiber (n = 1.4380) we obtain the largest tuning range of 98.4 nm as depicted in figure 3(*b*). Since the image is formed by the in-phase combination of the propagating modes, the reduction in the signal intensity is correlated with the loss of higher order modes due to reduced index contrast between core and liquid cladding. It is worth noting that a wider tuning could be achieved by slightly increasing the RI value, but even higher losses would need to be tolerated. Based on such results, it is feasible to use a liquid with an RI value that could compensate both previous effects and obtain a wide tuning range with minimum signal intensity variation. As shown in figure 3(*c*), a liquid with an RI of n = 1.434 provides such an effect allowing a tuning range of 68.6 nm with negligible signal variation. Also shown in figure 3(*d*) is the absolute wavelength shift for each liquid as a function of the liquid level around the no-core fiber. As shown in this figure, the tuning response is highly linear for each liquid. It is clear from figure 3(*d*) that a specific tuning range can be easily selected by choosing the adequate liquid RI value, which could be beneficial for some applications.

3. Tunable fiber lasers

In order to demonstrate the versatility of our optofluidically tunable MMI filter, two different gain media with different bandwidths were used. A tunable fiber ring laser was fabricated using 10 m of L-band erbium doped fiber (EDF) as the gain medium, whose schematic diagram is depicted in figure 4 (left). One end of the optofluidically tunable MMI filter was spliced to the L-band fiber while the other end was spliced to the input of a 10/90 fiber coupler. The 10% output allowed us to continuously monitor the lasing spectral response, and it was acquired by using an optical spectrum analyzer (OSA) from Agilent working at 0.06 nm resolution. The 90% output arm is spliced to the input of an optical isolator to keep the laser unidirectional, while the isolator output is spliced to a 980/1550 wavelength division multiplexer (WDM). The ring is closed through splicing the WDM output to the L-band EDF. A 980 nm wavelength laser diode with a pump power of 150 mW from Lucent Technologies is used to pump the L-band EDF through the WDM fiber coupler.

The MMI device was fabricated by splicing a 57.70 mm long section of no-core fiber between two SMF. Such a length provides a peak wavelength close to 1560.0 nm, which sets the starting point of the tuning range. Since a tuning range close to 60 nm is expected from this gain medium, we choose a liquid with an RI value of 1.4300. The liquid level was increased in steps of 5 mm, and the lasing spectrum was acquired at each step. Figure 5(*a*) plots the superimposed laser output spectra at different liquid levels, in which the spectra are shown for

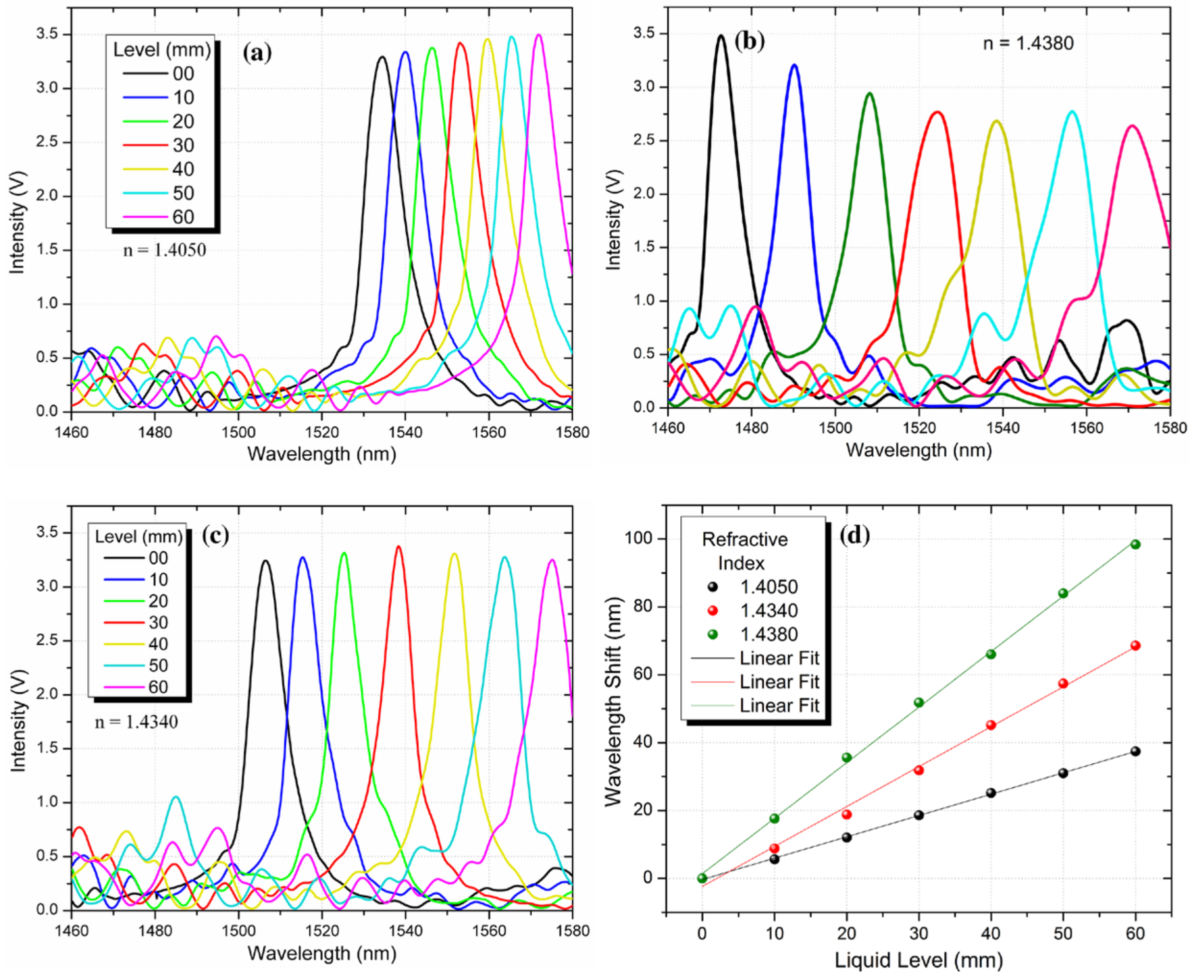

Figure 3. Spectral response of the optofluidically tunable MMI filter for different liquid levels for (*a*) $n = 1.4050$, (*b*) $n = 1.4380$, (*c*) $n = 1.4340$, and (*d*) total wavelength shift as a function of the liquid level for the three liquids.

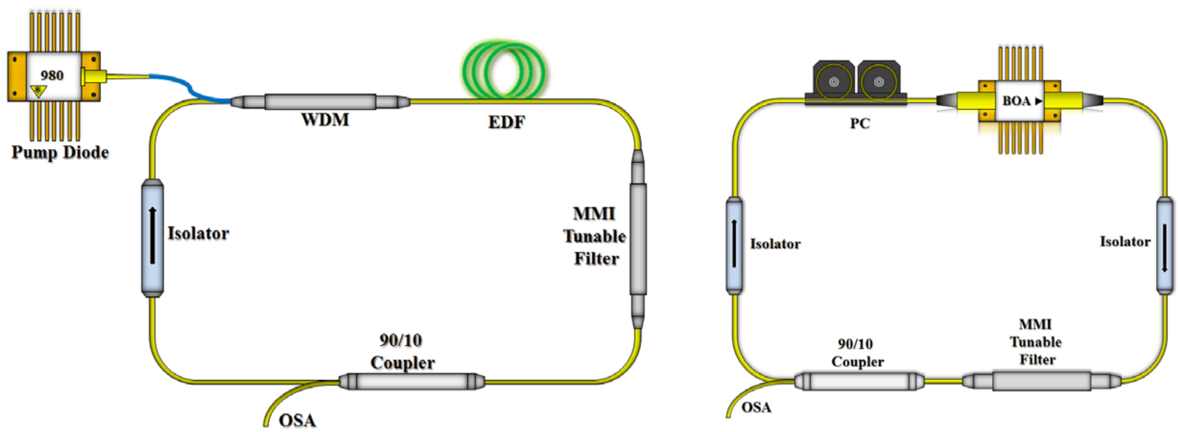

Figure 4. Experimental set-up of the optofluidically tunable MMI EDF laser (left), and experimental set-up of the optofluidically tunable MMI BOA fiber laser (right).

liquid increments of 10 mm for better appreciation. As shown here, the lasing line are tuned over 55 nm from 1559.4 to 1614.4 nm while the side-mode suppression ratio (SMSR) is maintained at a value exceeding 50 dBm over the whole tuning range. The measured line width of the tunable laser output is less than 0.18 nm. The peak wavelength as a function of the liquid level is also shown in figure 5(*b*), where we can observe a linear tuning response. Although the gain spectrum of the EDF is uneven, the output power difference among all lasing lines is less than 0.76 dBm.A broader gain medium can be achieved by replacing the gain medium with an SOA. We used the booster optical amplifier (BOA) BOA 1004 from

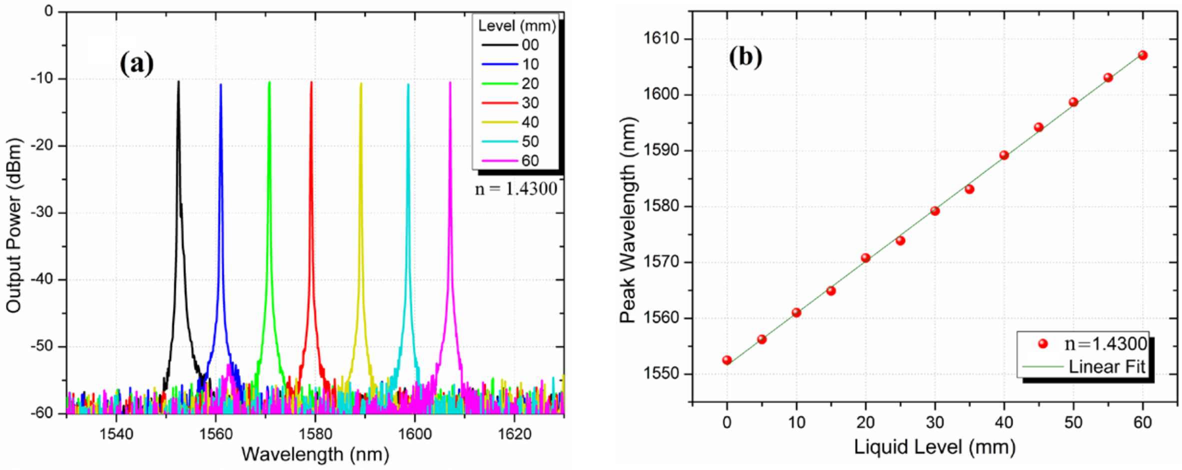

Figure 5. (*a*) Superimposed spectral response of the optofluidically tunable MMI EDF laser, and (*b*) peak lasing wavelength against liquid level.

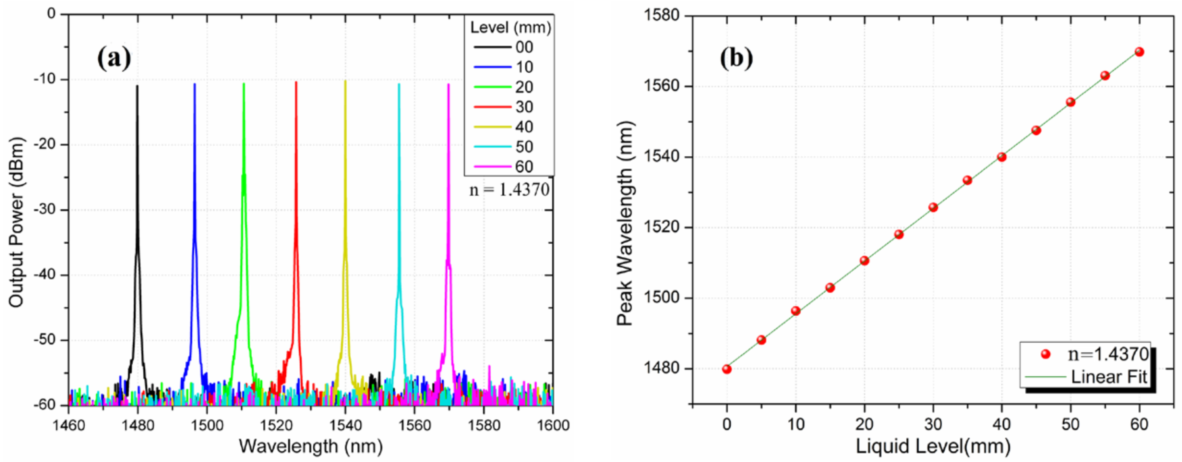

Figure 6. (*a*) Superimposed spectral response of the optofluidically tunable MMI BOA fiber laser, and (*b*) peak lasing wavelength against liquid level.

COVEGA that provided a bandwidth slightly wider than 90 nm and an even gain profile. As shown in figure 4 (right), the BOA replaces the pump diode, WDM and EDF, and since it has fiber pigtails, it can be easily spliced into the ring cavity. A polarization controller has to be added to the ring because the BOA is polarization dependent. Another isolator has to be included in the cavity to eliminate some resonances that are observed due to some reflections into the BOA. In this case the MMI filter consisted of a no-core length of 60.98 mm, which corresponds to a peak wavelength of 1480 nm, and we selected a liquid with an RI value of $n = 1.437$ to obtain close to 90 nm tuning. As shown in figure 6(*a*), we can tune the laser over 90 nm while maintaining a low output power variation below 0.73 dBm. The measured line width of the tunable laser output is less than 0.07 nm. Also shown in figure 6(*b*) is the peak wavelength against the liquid level, and again the tuning response remains highly linear. We should emphasize that even when our MMI filter is operating within the 1550 nm window, it could be operated at any wavelength as long as the fiber transmits light at such a particular wavelength window. Any other gain medium that is not fiberized could make use of an external coupling scheme and take advantage of our filter capabilities.

4. Conclusions

We demonstrated a wide range optofluidically tunable MMI fiber laser. The advantage of this tuning mechanism is related to its wide tuning range, highly linear response, as well as the ability to select the tuning range by changing the RI of the liquid. We demonstrated the versatility of our filter by tuning two different gain media, EDF and SOA, achieving tuning ranges of 55 and 90 nm respectively. In both cases, we achieve an SMSR better than 50 dBm with output power variations of less than 0.76 dBm.

Acknowledgments

We sincerely appreciate the support from the Consejo Nacional de Ciencia y Tecnología (CONACyT) under contracts

CB-2010/157866 and CB-2008/101378. JEAL acknowledges CONACyT for their support through a postdoctoral scholarship.

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