Wavelength Tuning of Multimode Interference Fiber Lasers: A Review

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Herein, the main aspects of fiber lasers are summarized where multimode interference (MMI) is the underlying phenomenon for the wavelength tuning mechanism. Also, 15 years of work in the field are covered, from its first report, in 2005, to the most recent publications, in 2020. In addition to the historical perspective, insights into the different mechanisms are also provided that are exploited to tune the spectral response of the MMI filters used in fiber lasers, among which are free space, optofluidic, stress optic, thermo optic, and nonlinear mechanisms.

1. Introduction

The self-imaging phenomenon was first observed by Talbot[1] and explained by Rayleigh[2] in diffraction from gratings. Since then, the field has been consolidating until a solid understanding has been achieved.[3–6] For some time, self-imaging phenomena were restricted image formation to free-space applications.[7,8] However, it was soon recognized that the same effects could be observed in waveguides supporting multiple modes. The above opened the venue for photonic integrated devices based on these multimode interference (MMI) effect.[9,10] Examples of these are N-by-N couplers/splitters on different material platforms, asymmetric splitters for power monitoring, polarization beam splitters, and devices based on biopolymer waveguides. Regarding optical fiber technology, originally, MMI phenomena were used to optimize the transmission through fiber links. Later on, optical fiber-based devices with more flexible functionalities were developed, such as tunable fiber lenses[11] and bandpass filters.[12]

Nowadays, the use of fiber optics MMI devices has been popularized mainly due to ease of fabrication: in its simplest form, it requires only sandwiching a multimode fiber (MMF) between two single-mode fiber (SMF) ones. All the aforementioned ones allow for simple, robust, and highly reproducible fiber-based devices. Also, MMI devices’ performance, including their spectral response, depends on both geometrical and optical parameters. These parameters allow multiple degrees of freedom to manipulate and control MMI devices, making them extremely versatile in applications. Moreover, MMI phenomena are present in the entire electromagnetic spectrum which, consequently, allows scaling MMI devices while keeping their functionality.

In this Review, we focus our attention on MMI tunable fiber lasers. We summarize the main aspects of more than 20 reports, covering 15 years of work in the field, where MMI is the underlying phenomenon for the wavelength tuning mechanism. We review several mechanisms that have been exploited to tune the spectral response of the MMI filters used in fiber lasers, among which are free space, optofluidic, stress optic, thermo optic, and nonlinear mechanisms. As it will be evident throughout this Review, this is a growing field, as shown in Figure 1, where the cumulative number of papers published on wavelength-tuned MMI fiber lasers is plotted over time, starting from the first report, in 2005, to the most recent publications, in 2020.

2. Overview of Wavelength Tuning Mechanisms of MMI Fiber Lasers

The filter-like spectral response of a simple fiber optics MMI device consisting of a section of MMF excited by an SMF, under conditions of symmetric interference, namely when the MMF is excited at its center by the radially symmetric input field of the SMF, is governed by the following expression[9]

$$\lambda_{\text{peak}} = p n_{\text{eff}} W_{\text{eff}}^2 / L_{\text{eff}}$$

(1)

This expression allows calculating the peak wavelength $\lambda_{\text{peak}}$ that will replicate the pth self-image of the input field in an MMI device of effective length $L_{\text{eff}}$, effective refractive index (RI) $n_{\text{eff}}$, and effective optical diameter $W_{\text{eff}}$, which can be estimated by correcting the physical diameter, $W$, with the
penetration depth of the evanescent tails into the cladding as\(^{[9,10]}\)

\[
W_{\text{eff}} = W + \frac{1}{2} \left( \frac{\lambda_0}{\pi} \right) \left( n_c^2 - n_l^2 \right)^{\frac{1}{2}} \left( \frac{n_c}{n_l} \right)^2 + 1 \tag{2}
\]

where \(n_c\) and \(n_l\) is the RI of the core and the cladding, respectively, of the MMF; \(\lambda_0\) is the free-space wavelength; and \(W\) is the geometrical diameter of the MMF. Note that, \(n_c\), \(n_l\), and \(W_{\text{eff}}\) are implicit functions of the wavelength. For most practical situations, the second term in Equation (2) represents a correction smaller than one wavelength. Therefore, the approximation \(W_{\text{eff}} \approx W\) holds a reasonable estimate for cases when the MMF’s core is much larger than the wavelength.

Despite its simplicity, Equation (1) provides explicit hints for some of the mechanisms that can be used to change the spectral response of an MMI filter, such as RI variations and strain. For instance, if one changes \(n_l\) or \(n_c\) of the MMF, without altering the geometrical parameters, then a change in \(\lambda_{\text{peak}}\) will be determined by the change induced to \(n_{\text{eff}}\). In experiments, both \(n_l\) and \(n_c\) can be easily manipulated, as discussed in the following paragraphs. If the MMF is subjected to strain or compression such that the MMF becomes effectively longer or shorter, then a change in \(\lambda_{\text{peak}}\) will be determined by the change induced to \(L_{\text{eff}}\).

**Figure 2** shows the different mechanisms that have been used to tune the spectral response of the MMI filters used in fiber lasers. For instance, free-space mechanisms allow varying \(L_{\text{eff}}\) by letting the light leave the fiber and propagate the desired path in air, and then coupling it back with the help of a mirror. Regarding optofluidic mechanisms, both \(n_{\text{eff}}\) and \(L_{\text{eff}}\) can be influenced. For instance, using a cladding-less MMF, one can induce variations on \(n_{\text{eff}}\) by changing the RI of the surrounding liquid, which effectively plays the role of the MMF cladding. Alternatively, one can make a liquid section that effectively plays the role of an extension of the MMF and can help to modify \(L_{\text{eff}}\) dynamically by displacing it. In terms of stress-optic mechanisms, both \(n_{\text{eff}}\) and \(L_{\text{eff}}\) can be influenced as well.

All these mechanisms will be discussed in more detail in the following text, as the different reports are reviewed.

3. Wavelength-Tuned MMI Fiber Lasers

3.1. Free Space

The first demonstrations of wavelength tuning of fiber lasers using MMI effects were done using free-space mechanisms. Essentially, the parameter of the MMI filter that is influenced is \(L_{\text{eff}}\).

Selvas et al. demonstrated the tuning of an ytterbium (Yb) MMI fiber laser, in reflection, by placing a mirror in front of the facet of the MMF\(^{[13]}\). \(L_{\text{eff}}\) makes the MMI filter’s self-image to form at a different wavelength by displacing the mirror, displacing its spectral response. With this approach, they demonstrated laser tuning over 8 nm, ranging from 1088 to 1097 nm, in continuous-wave (CW) operation with a single laser output.

A year later, Anzueto et al. demonstrated a similar Yb MMI fiber laser, in reflection, with several improvements, especially to overcome misalignment errors\(^{[14]}\). They coated the facet of an MMF with gold, basically making the mirror to be part of the fiber. Then, they fabricated a polymer channel where the optical fibers remain aligned at all times while the gold-coated MMF is displaced. They demonstrated laser tuning over 12 nm, ranging from 1083 to 1095 nm, in CW operation with a single laser output.
Finally, using a similar operation principle like Anzueto et al., in 2008, Castillo et al. demonstrated an erbium (Er) MMI fiber laser.\cite{26} They achieved laser tuning over 17 nm, ranging from 1558 to 1575 nm, in CW operation with a single laser output.

### 3.2. Optofluidic

In free-space implementations, the main disadvantage is the enormous losses and spurious reflections induced by making the light leave the fiber, even if alignment precautions are taken. To overcome these limitations, the next level of sophistication came with optofluidic mechanisms that allowed all-fiber implementations, where the light never leaves the fibers. Optofluidically, the parameters of the MMI filter that can be influenced are both \( L_{\text{eff}} \) and \( n_{\text{eff}} \).

In the first demonstration of optofluidic laser tuning, Castillo et al. constructed an MMI fiber laser where the MMF of the filter was aligned to the input SMF inside a silica ferrule filled with RI matching liquid.\cite{27} The fibers remain well-aligned inside the ferrule as one of the fibers is displaced, and instead of traveling in the air, the light now travels in a medium whose RI is close to that of the optical fibers, reducing spurious reflections and losses. The section of RI matching liquid acts as an extension of the MMF. This section can be made longer or shorter by displacing one of the fibers. In their demonstration, they changed the length of the MMI filter only by around 3%, and they were able to achieve laser tuning over 60 nm, in the range from 1549 to 1609 nm, in CW operation with a single laser output.

In this area of optofluidic tuning of MMI devices, we should mention that a typical approach that has become popular consists of using a so-called no-core fiber (NCF) as the MMF in the MMI device. An NCF is an optical fiber without a core whose cladding is the medium surrounding it whose use has been popularized in a number of applications.\cite{28} When used in an MMI filter, the spectral response can be tuned by changing the RI of the medium in which the NCF is immersed or, equivalently, by changing the portion of the NCF that is covered. In fact, using this liquid-level approach, Antonio et al. demonstrated laser tuning of an Er MMI fiber laser over a similar range of 35–60 nm, around 1550 nm, in CW operation with a dual laser output.\cite{29,30} A few years later, based on a similar liquid-level approach, the same team demonstrated a laser tuning over an extended range by using a booster optical amplifier (BOA) with wider bandwidth.\cite{31} They achieved laser tuning over 90 nm, ranging from 1480 to 1570 nm, in CW operation with a single laser output. Fundamentally, this tells that one could, in principle, use broader sources and still be able to design the operation of the MMI to higher-order self-images, i.e., larger values of \( p \) in Equation (1), to cover a large dynamic range.

In 2014, Ma et al. demonstrated the optofluidic tuning of an Er MMI fiber lasers by immersing the NCF-based MMI filter in an aqueous solution of ethylene glycol. In a first implementation, they immersed the MMI filter in the solution and dynamically changed the relative concentration of ethylene glycol to achieve the RI changes desired.\cite{32} They achieved laser tuning over 32 nm, ranging from 1532 to 1564 nm, in CW operation with a single laser output. In a second implementation, they used a similar optofluidic tuning by immersing the MMI filter in a liquid solution, but they also implemented a cascaded Sagnac loop filter to achieve dual-wavelength oscillation.\cite{33} This, together with the optofluidic tuning of the MMI filter, allowed them shifting the two laser peaks simultaneously with a single MMI filter. They achieved laser tuning over 40 nm, ranging from 1525 to 1565 nm, in CW operation with a dual laser output.

Later on, Ma et al. demonstrated a similar liquid-level optofluidic tuning of thulium (Tm) MMI fiber lasers by progressively immersing the NCF-based MMI filter in liquids of different RIs.\cite{34} They achieved laser tuning over 45 nm, ranging from 1815 to 1860 nm, in CW operation with a single laser output. A few years later, similar work was reported by Ibarra et al., where the laser output was dual.\cite{35} They immersed an NCF-based MMI filter in aqueous solutions of ethylene glycol with different concentrations and achieved laser tuning over 24 nm, in the range from 1828 to 1852 nm, in CW operation with a dual laser output. Finally, using an extensible liquid core between a pair of MMFs, in 2020, Sakata et al. demonstrated the optofluidic tuning of a Tm MMI fiber laser with over spectral windows complementary to those of previous reports.\cite{36} They achieved laser tuning over 57 and 64 nm, ranging from 1809 to 1866 nm and from 1866 to 1930 nm, respectively, in CW operation with a single laser output.

### 3.3. Stress Optic

Another commonly used way to wavelength tune MMI fiber lasers is based on stress-optic effects. In this case, the parameters of the MMI filter that can be influenced are both \( L_{\text{eff}} \) and \( n_{\text{eff}} \).

The first demonstration was from Walbaum et al., in 2011, where they tuned an Er MMI fiber laser by merely bending the section of MMF.\cite{37} In this case, \( n_{\text{eff}} \) becomes a function of the curvature. They achieved laser tuning over 11.6 nm, ranging from 1539 to 1550 nm, in mode-locking (ML) operation with a single laser output. A similar bending-based tuning was also demonstrated by Li et al., in 2016, where they demonstrated the tuning of a Tm MMI fiber laser, achieving laser tuning over 20 nm, around 1970 nm, in CW operation with a single laser output.\cite{38} A year later, in 2017, Ahmad et al., demonstrated a similar bending-based tuning of an Er MMI fiber laser, where they achieved laser tuning over 9.8 nm, in the range from 1552 to 1562 nm, in Q-switching (QS) operation with a single laser output.\cite{39}

In this area of stress-optic effects, another common approach consists in taking advantage of the inherent functionality of commercial-grade polarization controllers (PCs) to twist the section of MMF, producing a change mainly in \( n_{\text{eff}} \). By doing so, Mukhopadhyay et al., in 2014, demonstrated the stress-optic tuning of a Yb MMI fiber laser, achieving laser tuning over 32 nm, in the range from 1038 to 1070 nm, in CW operation with a single laser output.\cite{40} Following up on this work, a few years later, in 2017, Chakravarty et al., extended the laser tuning of a Yb MMI fiber laser to a QS operation.\cite{41} They achieved laser tuning over 16 nm, in the range from 1057 to 1073 nm. A similar PC-based stress-optic implementation was reported by Khattak et al., in 2018, where they coiled a long MMI filter (1 m-long) in a PC pad to tune an Er MMI fiber laser.\cite{42} They achieved laser tuning over 9.3 nm, ranging from 1555 to 1565 nm, in CW operation.
and a single output. Finally, a more sophisticated implementation was reported by Zhang et al., in 2019, where they tuned an Er MMI fiber laser using two MMI filters fused together, each stressed by its own PC, to achieve ML operation. They achieved laser tuning over 40 nm, ranging from 1533 to 1573 nm, in ML operation and a single output.

A different implementation was reported by Zhang et al., in 2015, where they used a PC together with a so-called fiber squeezer to tune a Tm MMI fiber laser, in such a way that now the main parameter of the MMI filter that is affected is $L_{\text{eff}}$. In this way, by simultaneously adjusting the PC and rotating the fiber squeezer, they achieved laser tuning of a Tm MMI fiber laser over 24 nm, ranging from 1892 to 1916 nm, in CW operation and a single output.

Table 1 shows the main parameters of the different MMI fiber lasers discussed throughout this Review. We tracked simultaneously the spectral window of operation, defined by the doping material, the wavelength range of operation, the tuning range achieved, the type of operation (CW, ML, and QS) and output (single or dual), the parameter of the MMI filter that is influenced in the experiments, and the type of mechanisms that are used to change such parameter of the MMI filter.

Complementarily, Figure 3 shows the central wavelength of operation and the range over which the MMI fiber laser was tuned, for all the MMI tunable fiber lasers discussed in this Review. They are sorted alphabetically by the spectral window of operation (Yb, Er, and Tm). Also, within each spectral window, the different reports are labeled in order of appearance in the literature. Finally, we labeled separately exceptional cases where an unusually large tuning range was achieved using special light sources consisting of several broadband emissions overlapped.

### 3.4. Nonlinear

A couple of implementations based on nonlinear mechanisms have been reported. These are peculiar implementations where nonlinear MMFs, e.g., graded-index MMF, are used in the MMI filter and allow for all-optical control. In the nonlinear regime, both self-phase and cross-phase modulation occur in the nonlinear MMF in addition to the wavelength selection. Depending on the nonlinear MMF used, even saturable absorption effects can take place as well. Because of these nonlinear effects, the propagation constants of the guided modes can be influenced by the input power, essentially affecting $n_{\text{eff}}$.

### Table 1. Summary of the relevant parameters of the wavelength-tuned MMI fiber lasers reviewed in this paper. The different reports are listed in order of appearance in the literature.

| #  | Ref.          | Doping | Tuning range [nm] | Wavelength range [nm] | Output type | Output power [mW] | MMI parameter | Mechanism     |
|----|---------------|--------|-------------------|-----------------------|-------------|-------------------|---------------|---------------|
| [13]| Selvas, et al. (2005) | Yb     | 8                 | 1088–1097             | CW Single   | 500               | $L_{\text{eff}}$ | Free-space    |
| [14]| Anzueto, et al. (2006) | Yb     | 12                | 1083–1095             | CW Single   | –                 | $L_{\text{eff}}$ | Free-space    |
| [15]| Castillo-Guzman, et al. (2008) | Er     | 17                | 1558–1575             | CW Single   | 2                 | $L_{\text{eff}}$ | Free-space    |
| [16]| Castillo-Guzman, et al. (2010) | Er     | 60                | 1549–1609             | CW Single   | 1                 | $L_{\text{eff}}$ | Opto-fluidic  |
| [19]| Antonio-Lopez, et al. (2012) | Er     | 35–60             | 1550                  | CW Dual     | 1                 | $n_{\text{eff}}$ | Opto-fluidic  |
| [20]| Mukhopadhyay, et al. (2014) | Er     | 32                | 1038–1070             | CW Single   | 0.3               | $n_{\text{eff}}$ | Stress-optic  |
| [21]| Ma, et al. (2014) | Er     | 32                | 1532–1564             | CW Single   | 0.1               | $n_{\text{eff}}$ | Opto-fluidic  |
| [22]| Ma, et al. (2014) | Er     | 40                | 1525–1565             | CW Dual     | 0.1               | $n_{\text{eff}}$ | Opto-fluidic  |
| [20]| Antonio-Lopez, et al. (2014) | Er     | 55                | 1559–1614             | CW Single   | 0.1               | $n_{\text{eff}}$ | Opto-fluidic  |
| [23]| Ma, et al. (2014) | BOA    | 90                | 1480–1570             | CW Single   | 0.1               | $n_{\text{eff}}$ | Opto-fluidic  |
| [33]| Zhang, et al. (2015) | Tm     | 45                | 1815–1860             | CW Single   | –                 | $n_{\text{eff}}$ | Opto-fluidic  |
| [27]| Li, et al. (2016) | Tm     | 20                | 1920–2020             | CW Single   | 0.3               | $n_{\text{eff}}$ | Stress-optic  |
| [30]| Chakravarty, et al. (2017) | Yb     | 16                | 1057–1073             | QS Single   | –                 | $n_{\text{eff}}$ | Stress-optic  |
| [38]| Ahmad, et al. (2017) | Er     | 9.8               | 1552–1662             | CW Single   | –                 | $n_{\text{eff}}$ | Stress-optic  |
| [31]| Khattak, et al. (2018) | Er     | 9.3               | 1555–1565             | CW Single   | –                 | $n_{\text{eff}}$ | Stress-optic  |
| [24]| Ibarra-Escamilla, et al. (2018) | Tm     | 24                | 1828–1852             | CW Dual     | –                 | $n_{\text{eff}}$ | Opto-fluidic  |
| [34]| Li, et al. (2019) | Er     | 27                | 1574–1601             | ML Dual     | –                 | $n_{\text{eff}}$ | Nonlinear     |
| [32]| Zhang, et al. (2019) | Er     | 40                | 1533–1573             | ML Single   | –                 | $n_{\text{eff}}$ | Stress-optic  |
| [25]| Sakata, et al. (2019) | Tm     | 57                | 1809–1866             | CW Single   | –                 | $L_{\text{eff}}$ | Opto-fluidic  |
| [35]| Li, et al. (2019) | Tm     | 5.2               | 1942–1947             | ML Single   | –                 | $n_{\text{eff}}$ | Nonlinear     |
| [36]| Sakata, et al. (2020) | Tm     | 100               | 1858–1958             | CW Single   | 2                 | $n_{\text{eff}}$ | Thermo-optic  |
|     | Tm             | 61                | 1954–2015           | CW Single   | 2                 | $n_{\text{eff}}$ | Thermo-optic  |
2019, Li et al. demonstrated an Er MMI fiber laser tuning over 27 nm, ranging from 1574 to 1601 nm, in an ML operation with a single output.\[^{34}\] In the same year, the same group reported a similar approach in a complementary spectral window, demonstrating a Tm MMI fiber laser tuning over 5.2 nm, ranging from 1942 to 1947 nm, in an ML operation with a single output.\[^{35}\]

### 3.5. Thermo Optic

Finally, to the best of our knowledge, only one report exist where MMI fiber lasers are wavelength tuned thermo optically. In 2020, Sakata et al. demonstrated the thermo-optic tuning of Tm MMI fiber lasers, where $n_{\text{eff}}$ was modified indirectly by changing the temperature.\[^{36}\] They used an NCF-based MMI filter placed inside a glass capillary filled with RI matching oil. This oil has a large thermo optic coefficient. By changing the whole structure’s temperature from 25 to 100 °C, they achieved laser tuning over 100 nm and 61 nm, in the range from 1858 to 1958 nm and from 1954 to 2015 nm, respectively, in CW operation with a single laser output.

### 4. Conclusion

In conclusion, this Review covers 15 years of work in the field of tunable MMI fiber lasers, from its first report, in 2005, to the latest, in 2020. We have extracted the most important aspects of more than twenty reports where MMI is the underlying phenomenon for the wavelength tuning mechanism.

Compared with other wavelength-tuning mechanisms for fiber lasers, the most predominant advantages of MMI-based ones are the following: 1) due to its easy fabrication, the MMI devices have been popularized in the past 15 years. In its simplest form, it only requires sandwiching an MMF between two SMFs. 2) MMI fiber devices are simple, robust, and highly reproducible. 3) Also, the performance of MMI devices, including their spectral response, depends on both geometrical and optical parameters. 4) The variations of $n_{\text{eff}}$ and $L_{\text{ eff}}$ of the multimode section allow having available multiples degrees of freedom to manipulate and control MMI devices, making them extremely versatile in applications. 5) The MMI phenomena are presented in the entire electromagnetic spectrum, which allows scaling MMI devices while keeping their functionality.

Essentially, we have reviewed five mechanisms to tune the spectral response of the MMI: free space, optofluidic, stress optic, thermo optic, and nonlinear mechanism. Some advantages and disadvantages among the different wavelength tuning mechanisms explored here are the following: free-space tuning constitutes the first demonstration; but, because the light leaves the optical fiber, the main disadvantages of these mechanisms are the misalignment errors, significant losses, and spurious reflections. This is corrected by all the other tuning mechanisms because the light remains confined at all times. Optofluidic mechanisms permit tuning over a broad wavelength range, but they have the main disadvantage of using liquid materials that evaporate or degrade over time. Moreover, some optofluidic implementations also require moving parts. Stress-optic-based tuning overcomes the limitations liquid materials, but it relies on moving parts that allow tuning over a narrower range. Nonlinear implementations allow for an all-optical control, overcoming the limitations of all other implementations, but only tuning over a narrow range has been demonstrated. In this regard, we would like to mention that, lately, attention has been attracted to using MMI filters in conjunction with saturable absorbers to achieve nonlinear tuning with a dual functionality of wavelength tuning and laser pulsing. Once again, in this Review, we considered reports where the tuning capabilities are explicitly demonstrated.

Finally, due to the presence of MMI phenomena across the electromagnetic spectrum, MMI devices can be scaled while keeping their functionality. For tunable fiber lasers, the main limitation has been the gain medium, not the tuning capabilities.
We noted that, historically, MMI tunable fiber lasers transitioned from gain media consisting of Yb-doped fibers (centered at 1080 nm); to Er-doped fibers (centered at 1580 nm); and then to Tm-doped fibers (centered at wavelengths >1800 nm); these last papers have been a breaking point in the cumulative number of papers published since 2014. We can also mention that the tuning range has been from 8 to 100 nm for the different tuning mechanisms of different gain media. The output type varies; it has been single- and dual-wavelength emissions; CW, ML, and QS. In all cases, the underlying tuning mechanism is MMI-based, and the structure of the MMI filters has been minimally modified.

Conflict of Interest
The authors declare no conflict of interest.

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