Passive athermalization of multimode interference devices for wavelength-locking applications

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Abstract: In this paper we demonstrate the passive, material-based athermalization of all-fiber architectures by cascading multimode interference (MMI) devices. In-line thermal compensation is achieved by including a liquid-core multimode section of variable length that allows ensuring temperature-independent operation while preserving the inherent filter-like spectral response of the MMI devices. The design of the temperature compensation unit is straightforward and its fabrication is simple. The applicability of our approach is experimentally verified by fabricating a wavelength-locked MMI laser with sensitivity of only $-0.1 \text{ pm/}^{\circ}\text{C}$, which is at least one order of magnitude lower than that achieved with other fiber optics devices.

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1. Introduction

Temperature-insensitive operation is often beneficial and many times crucial in several optical applications ranging from filtering, tuning, and switching to wavelength locking in laser systems and stability of light sources [1–5]. These applications are typically associated to the telecom industry, however, they can be extended to other areas such as sensing [6] since the overall performance of the optical systems in these applications relies on the operation of sub-units consisting of interferometers, resonators, gratings, (de)multiplexers, couplers, and switches, among others, which naturally imposes a temperature dependence.

Cancellation of thermal effects in this context has been approached by active means using thermo-electric heaters/coolers. Despite the feedback mechanisms tend to be complex in these active schemes successful operation has been demonstrated [7]. However, passive means are preferred not only to avoid additional power consumption and eliminate instrument footprints but also for integration feasibility.

Plentitude of examples of passive athermalization can be found in applications related to wavelength-locking [8–10], especially for wavelength division multiplexing (WDM) and silicon photonics [11–16]. In the case of wavelength locking, a common approach is the thermal compensation by means of gratings e.g. fiber Bragg gratings (FBGs), encapsulated such that the thermal effects are counterbalanced with mechanical stress due to thermal expansion or contraction. On the other hand, in silicon photonics the approach typically involves the use polymer-coated waveguides that allow compensating the large thermo-optic
coefficient (TOC) of silicon. By integrating waveguides with different TOC and adjusting their length, temperature independence can be achieved since the overall performance in these devices depends on the phase difference and not on the absolute phase shift [17].

Optical fiber devices are particularly attractive since unsophisticated, commercial-grade equipment such as splicers and fiber cleavers are typically required for their fabrication. However, thermal issues are also a concern for fiber-based devices and can be severely detrimental for telecom applications. Therefore, different approaches can be implemented to eliminate such thermal effects. In the case of configurations based on FBGs the thermal sensitivity of the devices has been reduced by a number of different approaches including the use of single-material structures [9] and multi-material composites [8, 10] with effective TOC of opposite sign to the one that is to be compensated. In some cases, some material from the cladding of the optical fiber has to be removed e.g. by wet etching, to induce the interaction of the evanescent tails with an external medium having TOC of opposite sign (to that of silica) [18]. In all cases, the minimum thermal sensitivity is still larger than 10 pm/°C which makes them unsuitable for applications where a tight control on the spectral shift is required.

Another possibility for all-fiber athermal platforms consists on the use of devices based on multimode interference (MMI) effects. These optical fiber devices are attractive due to manufacturing simplicity as their architecture typically consist on a series of spliced sections of single mode (SMF) and multimode (MMF) fibers e.g. SMF-MMF-SMF. The temperature dependence of these MMI devices have been reduced by following similar approaches than those used in the case of grating-based devices. For instance, thermal compensation down to 1 pm/°C has been demonstrated by packing the fiber in a host material e.g. ceramic, with TOC of opposite sign to that of silica [19]. Additionally, thermal compensation can be achieved by appropriately designing doping rates in the core of the optical fiber e.g. concentration of P2O5 and GeO2, as it has been reported for a MMF with parabolic index profile [20]. Moreover, the inherent nature of the architecture of MMI devices suggests that thermal compensation may be achieved by cascading sections of MMF with different thermal response and appropriate lengths [21]. In the case of MMI devices the thermal dependence has been decreased about one order of magnitude with respect to grating-based devices i.e. to about 1 pm/°C, which proves the efficiency of this approach.

In this paper we demonstrate passive, material-based athermalization of fiber-based architectures by employing multimode interference (MMI) devices with cascaded multimode fiber sections. In order to achieve and ensure thermal compensation a liquid-core multimode section of variable length is used that allows temperature-independent operation while preserving the inherent filter-like spectral response of the MMI devices. The applicability of our approach is experimentally verified by building a wavelength-locked MMI laser with sensitivity of only 0.1 pm/°C, capable to operate over tens of degrees Celsius of temperature change with minor variations in the lasing wavelength of only a few picometers.

2. Principle of operation

The self-image formation for MMI fiber devices has been widely investigated and is known to be governed by the relation expressed in Eq. (1) [22, 23]:

$$\lambda_{\text{peak}} = p \left( \frac{n_{\text{eff}} W_{\text{eff}}^2}{L} \right).$$

This expression allows calculating the peak wavelength $\lambda_{\text{peak}}$ that will replicate the p-th image of the input field in a MMI device of length $L$, effective refractive index $n_{\text{eff}}$, and effective optical diameter $W_{\text{eff}}$. The effective optical diameter $W_{\text{eff}}$ can be estimated by correcting the nominal diameter $W$ of the MMF with the penetration depth of the evanescent tails into the cladding by the following expression:
where $\lambda_0$ is the free-space wavelength, $n_c$ and $n$ are the refractive indexes of the core and cladding of the MMF at $\lambda_0$, respectively, and $W$ is the nominal diameter of the MMF i.e. physical diameter. The refractive indices and the optical diameter are implicit functions of the wavelength. The parameter $\sigma$ refers to the state of polarization and is taken as $\sigma = 0$ for TE and $\sigma = 1$ for TM. The estimate in Eq. (2) was derived for planar waveguides and thus polarization effects are to be considered, as indicated by the parameter $\sigma$. In order to use this estimate for circularly symmetric multimode waveguides, such as in the case of a MMF, one can simply average the optical diameters corresponding to the two polarizations i.e. $W_{\text{eff}} = (W_{\text{eff,TE}} + W_{\text{eff,TM}})/2$, for a reasonable approximation.

From Eqs. (1) and (2), it can be readily noticed that any change in the optical and/or the geometrical parameters of the MMF will result in a net shift of the peak wavelength. Based on this simple argument, one could think of designing a MMI device consisting of several cascaded multimode sections such that, by controlling the parameters of each MMF section, one could either maximize or cancel out the net shift in the spectral response of the MMI device. These two scenarios are desired, for instance, in sensing and stabilization, respectively. In this work we focus on the design of temperature-insensitive MMI devices.

Let us consider the most general case of a MMI device consisting of $N$ chained multimode sections, such as the one illustrated in Fig. 1.

Fig. 1. Passive, material-based cancellation of thermal effects achieved by cascading MMI devices having multimode sections with effective thermo-optic coefficients of opposite sign.

We can reformulate the expression in Eq. (1) to calculate the corresponding peak wavelength that will replicate the p-th image of the input field throughout the cascaded structure as follows:

$$
\lambda_{\text{peak}} = p \sum_{i=1}^{N} \left( \frac{n_{\text{eff},i} W_{\text{eff},i}^2}{L_i} \right) \left( \frac{L}{L} \right) \text{ with } \frac{1}{L} \sum_{i=1}^{N} L_i = 1.
$$

(3)

where $L_i$ is the length of the i-th multimode fiber section. The term $L/L$ fraction of this i-th multimode fiber section with respect to the total length of multimode fiber. If we now introduce the thermal dependence of this compound structure we get the following expression

$$
\lambda_{\text{peak}} + \Delta \lambda = p \sum_{i=1}^{N} \left( \frac{n_{\text{eff},i} + \Delta n_i}{L_i + \Delta L_i} \right) \left( \frac{W_{\text{eff},i} + \Delta W_i}{L_i + \Delta L_i} \right)^2 \left( \frac{L_i + \Delta L_i}{L + \Delta L} \right).
$$

(4)

where $\Delta L$ relates to the linear size change in the length resulting from thermal expansion and is subjected to $\sum_i \Delta L_i = \Delta L$ ; $\Delta n$ is the refractive index change of the material due to the thermo-optic effect, and $\Delta \lambda$ is the net shift of the spectral response of the MMI device (with respect to the design peak wavelength $\lambda_{\text{peak}}$) due to the thermal effects. It is important to notice that $\Delta W$, according to Eq. (2), contains contribution from both thermal expansion and thermo-optic effect.

The contributions from the thermal expansion terms in Eq. (4), $\Delta L$ and $\Delta W$, are typically positive (unless the materials involved in the structure shrink with temperature i.e. thermal contraction). On the other hand, the refractive index change $\Delta n$ can be either positive or
negative depending only on the sign of the TOC of the material of the i-th MMF section. For the case of negative TOC $\Delta n$ is negative and therefore the peak wavelength shifts towards smaller values. In practical cases in which the thermo-optic effect is orders of magnitude larger than the thermal expansion the analysis can be simplified by attributing the overall effect only to the thermo-optic contribution [19].

This straightforward manipulation of the sign of the contribution from each MMF section, together with the fact that usually the thermal expansion effect is significantly smaller than the thermo-optic effect, is what allows achieving conditions of full thermal compensation in which the net wavelength shift is zero within a range of temperatures. In fact, this condition of thermal compensation has been suggested both theoretically [24] and experimentally [25] for similar structures.

We would like to emphasize the usefulness of this general estimation in designing arbitrary cascaded MMI structures. However, in practical applications we usually look for architectures that help to simplify the fabrication process and ensure the repeatability of the experiments. In this context, the simplest cascaded MMI device is that consisting of a two-section architecture. In order to increase the flexibility of such a simple architecture in terms of both tunability and thermal compensation, we propose a cascaded structure composed by a standard silica MMF followed by a silica capillary tube filled up with a material with TOC of opposite sign, as it is schematically depicted in Fig. 2.

Attempts of thermal compensation using similar concepts to those discussed above have been reported [21]. The novelty of our approach relies in that the incorporation of a liquid-core multimode section of variable length allows i) ensuring temperature-independent operation ii) while preserving the inherent filter-like spectral response of the MMI devices.

The material inside the capillary, in general, can be anything as long as both the sign of the TOC allows for thermal compensation and the material is suitable for operating in the temperature range of interest i.e. it does not damage or evaporate. Typical materials include polymers and refractive index matching liquids, among others, due to their large negative TOC, thermal stability, and the wide range of the materials’ optical and mechanical properties currently available. In this work we will study the particular case of the liquid-core MMF.

From Eq. (4), one can analytically calculate the peak wavelength response of a two-section i.e. solid-liquid, MMI cascade in which thermal effects are considered. Taking advantage that a liquid section can be in principle of variable length, the condition of full thermal compensation can be found by simply computing the spectral wavelength shift for pairs of temperature and length of the liquid section (for a fixed length of the solid section).

In the following, we illustrate our proposal by a simple simulation that shows thermal compensation for the practical example of a solid-liquid architecture consisting of a standard 105 µm-core silica MMF followed by a 127 µm-diameter capillary tube filled with refractive index matching oil. In the solid section (silica), the thermal expansion effect ($5 \times 10^{-7} \text{°C}^{-1}$) is almost two orders of magnitude lower than the thermo-optic effect ($1 \times 10^{-5} \text{°C}^{-1}$). The refractive index of the core and the cladding in this solid section are taken as 1.4575 and 1.4440, respectively, at the design wavelength of 1550 nm. This results in a numerical aperture of 0.22 which is typical in standard MMF. In the liquid section the refractive index of the core and the cladding in are taken as 1.5320 and 1.4440, respectively, at the design
wavelength of 1550 nm. In this section the dominance of the thermo-optic effect is more pronounced since the contribution from thermal expansion is the same as in the solid MMF i.e. it is the silica capillary tube that expands, while the magnitude of the TOC of the liquid-core is on the order of \(-10^{-4} \, ^\circ\text{C}^{-1}\). In the calculations, the TOC of the liquid is taken as \(-2.15 \times 10^{-4} \, ^\circ\text{C}^{-1}\) which is in good agreement with typical values in manufacturers’ datasheets.

Figure 3 shows the net shift of the peak wavelength, \(\Delta \lambda_{\text{peak}}\), for pairs of temperature and length of the liquid section in the range from 25 °C to 150 °C and from 0 mm to 3 mm, respectively. The color bar indicates the absolute value of the spectral shift of the MMI structure, in nm. The condition of thermal compensation is given by the length of the liquid section that results in zero wavelength shift. In this particular example, as shown in Fig. 3, athermal MMI operation is achieved when the liquid section has a length of 1.5 mm.

3. Experiments and results

Proof-of-concept experiments consisted on demonstrating the thermal compensation of a laser cavity using the ring configuration schematically shown in Fig. 4. This all-fiber ring cavity is based on a standard configuration in which a section of erbium-doped fiber (EDF) is used as the gain medium. Briefly, in the standard ring cavity configuration a 980 nm laser diode is used to pump the EDF using a 980/1550 nm wavelength-division-multiplexing device (WDM) and a 90/10 out-coupler is used to monitor the spectral content of the laser emission in an optical spectrum analyzer (OSA). Also, in order to ensure directionality an isolator is introduced between the WDM and the 90% output of the out-coupler. The WDM used in the experiments (JDSU model IWDMC1111AA40) operates in the forward pump mode i.e. the pump is sent to the EDF immediately after the WDM for maximum utilization of the pump, and the circulation within the cavity is counterclockwise, as indicated. The all-fiber MMI-based thermal compensation unit was included in this standard lasing configuration as shown schematically in Fig. 4 for the in-line athermalization of the cavity.

In our experiments we used a 10m-long section of L-band EDF (0.25 NA and dopant concentration of 3000 ppm) and, in order to minimize the losses, the WDM, the EDF, the isolator, and the out-coupler were spliced. Also, the EDF was spliced to the solid end of the thermal compensation unit (solid MMF). In this way, the only ‘movable’ parts of the setup that are allowed to be aligned during the experiments are the solid MMF and the output SMF that are inside the liquid-filled capillary. The capillary has an internal diameter of about 127 \(\mu\text{m}\) and therefore the misalignment between the solid MMF and the output SMF is not critical.
in any case. The small adjustments in the alignment simply allow for optimum out-coupling of the light into the SMF.

Fig. 4. Erbium-doped fiber ring-laser configuration with the thermo-optic compensation unit.

3.1 Fabrication of the temperature-compensation unit

The fabrication of the solid-liquid MMI is simple and allows for consistent repeatability. The fabrication starts from splicing a section of standard 105/125 MMF to the SMF coming from the EDF. The length of this MMF determines the laser operation wavelength if only the solid section is considered and it has to be selected such that the peak of the MMI filter response falls within the linewidth of the L-band emission of the EDF.

An additional consideration has to be taken into account at the moment of selecting the length of the solid MMF since the liquid section that will be later introduced effectively results in a shift of the MMI filter response towards shorter wavelengths due to the increased length. Strictly speaking, as explained in the previous section, thermal compensation can be achieved regardless of the length of the solid MMF by simply adjusting the length of the liquid section (see Eq. (4)). However, one should exert care in designing the thermal compensation cell such that the overall response of the compound solid-liquid MMI structure falls within the linewidth of the L-band emission of the EDF and also operates within the desired spectral window.

In our experiments, the length of the solid MMF is 41.2 mm for a baseline filter response centered about 1587 nm. This length of MMF remained the same throughout the experiments i.e. same piece of MMF at all times, and only the length of the liquid section was increased until athermal operation was achieved. Recall the peak wavelength decreases with increasing length of the device so when the length of the liquid section is increased in the experiments a shift of the filter response towards shorter wavelengths is expected.

After cleaving the MMF, the free end of this MMF section is introduced into a capillary with internal and external diameter of 127 µm and 2 mm, respectively. Once the MMF is positioned within the capillary, the capillary was fixed to a metallic plate and filled with refractive index matching oil (Cargille, index of 1.529 at 1588.5 nm and TOC of $-4.16 \times 10^{-4}$ °C$^{-1}$). Once the capillary has been filled, the output SMF (fiber going to the 90/10 out-coupler) is inserted into the capillary from the other side until it touches the (previously positioned) solid MMF. The position of both the solid MMF and the output SMF is independently controlled by means of XYZ translation stages, as shown in Fig. 4. As mentioned before, the solid MMF and the output SMF are practically aligned within the capillary and the fine adjustments permitted by the translation stages are only for out-coupling optimization.
3.2 Experimental results

The initial configuration of the experiment is that in which the length of the liquid section is approximately zero i.e. output SMF in contact with the MMF within the capillary. From this point on, the experiment consists on setting a fixed length of the liquid MMF section i.e. fixed separation between the solid MMF and the output SMF within the capillary, and record the spectrum of the laser emission at different temperatures to verify the condition of thermal compensation. Throughout the experiments the temperature was controllably increased from 25 °C to 95 °C in steps of 25 °C. At each temperature point sufficient time (20 min) was allowed for reaching thermal equilibrium.

Figure 5 shows the experimental results for different lengths of the liquid section. In the experiments, the length of the solid MMF is 41.2 mm and the length of the liquid section was kept fixed for each temperature swept in order to verify the temperature dependence of the laser emission for a particular solid-liquid combination. Figure 5(a) shows the laser emission for the initial condition of the experiment in which the facets of the MMF and the SMF are in contact i.e. the length of the liquid section is approximately zero. In this case, the spectral shift is determined almost entirely by the TOC of the solid MMF. The total shift of the laser emission is of 1.24 nm for the temperature variation from 25 °C to 95 °C. Figures 5(b) and 5(c) shows the net spectral shift of the laser emission of 0.67 nm and 0.23 nm for lengths of the liquid section of 700 µm and 1200 µm, respectively. Here the progress towards athermal operation can be clearly appreciated as the total spectral shift when the liquid section is included reduces to about one half (Fig. 5(b)) and one fifth (Fig. 5(c)) of the initial wavelength shift as compared with the structure that consists only of the solid section (Fig. 5(a)). Figure 5(d) shows the condition of full thermal compensation achieved with a length of the liquid MMF of 1500 µm. In this case the spectral shift of the laser emission is practically cancelled for the temperature range from 25 °C to 95 °C and the laser peak exhibits an absolute wavelength variations of only 7 pm. This is an outstanding result since the variation of the laser wavelength is only a few picometers over tens of degrees Celsius of temperature variation.

![Figure 5. Erbium laser emission at different temperatures for different length of the liquid section as indicated in each panel. The inset in panel (d) shows a zoom-in into the peaks of the laser](image.png)
emission for the different temperatures in the condition of thermal compensation. The temperature labels in (d) are the same as in the other panels.

Figure 6 summarizes the net wavelength shift of the laser emission (see Fig. 5) as a function of temperature obtained for structures with liquid section of different length (in all cases, the solid section was 41.2 mm). Since the net wavelength shift varies linearly with temperature the thermal dependence of the experimental setup can be calculated directly from the slope. In all cases the linear regression analysis of the experimental data points shows a good fit ($R^2>0.99$ in all cases). As shown in Fig. 6, for a length of 1500 µm the thermal effects are practically cancelled.

Our experimental results show that the thermal response of the device, i.e. wavelength shift per unit temperature, is only $-0.1$ pm/°C. It is worth noting that in our experiments standard micrometers were used for controlling the separation between the optical fibers. With a more sophisticated and accurate positioning mechanism e.g. translation stages with better spatial resolution, full thermally-compensated devices in which the temperature dependence is completely cancelled are feasible.

![Fig. 6. Net wavelength shift of the laser emission as a function of temperature for different lengths of the liquid multimode section (constant solid section of length 41.2 mm at all times). The thermal dependence of the experimental setup for each case can be calculated from the slope of the straight line as indicated.](image)

Given the nature of the cascaded structure used here, it is expected that our results are comparable with similar structures [19–21], which indeed is the case. Nevertheless, the key difference in our approach is that the length of the liquid multimode section can be changed dynamically which allows i) ensuring temperature-independent operation ii) while preserving the inherent filter-like spectral response of the MMI devices. This provides an extra degree of freedom that allows ensuring a condition of full thermal compensation.

The extremely low thermal sensitivity demonstrated here ($-0.1$ pm/°C) is one order of magnitude smaller than the lowest one reported for fiber devices. Moreover, this sensitivity is similar to that achieved in silicon photonics applications in which the target sensitivity is typically $<1$ pm/°C. Some examples of devices for which this low temperature sensitivity is critical are wavelength-division multiplexers (WDM) and ring micro-resonators. In this cases, thermal compensation is typically achieved by covering the silicon waveguides with polymer coatings i.e. polymer claddings [11, 26, 27], as well as interferometric filters with dedicated geometrical designs i.e. optimization by variations in the dimensions of the arms of the interferometers [28].

Regarding the particular configuration used in our experiments i.e. liquid filled capillaries, we should note that polymer-filled capillaries would also allow for all-fiber, thermally-
compensated structures that can in principle be spliced. Depending upon the polymer used, these structures could operate even at higher temperatures or extended temperature ranges. Nevertheless, care should be taken in designing these structures not only because of their fixed length (the degree of freedom of the variable length is lost) but also because expansion/contraction thermal effects must be taken into account to avoid damage due to mismatch in the expansion coefficients of the materials.

4. Conclusions

In this paper we demonstrated the passive, material-based athermalization of all-fiber architectures by means of cascaded MMI devices. Thermal compensation is achieved by including a liquid-core multimode section of variable length that allows ensuring temperature-independent operation while preserving the inherent filter-like spectral response of the MMI devices.

Using this approach the wavelength-locking of a MMI fiber laser was experimentally demonstrated with temperature sensitivity of only 0.1 pm/°C. This value is one order of magnitude smaller than the lowest sensitivity reported to date for fiber devices and is actually comparable to values achieved in silicon photonics applications by special polymer coatings and dedicated interferometric designs.

We emphasize that even when very low temperature dependence can be achieved it is also desired to preserve the well-known versatile and robust tuning of the inherent filter-like spectral response of MMI-based [29, 30], which has been actually used to tune laser emission over a broad wavelength range in similar cavity configurations [23, 31]. This forces one to raise the question of whether it is possible to have full thermal compensation while preserving tunability. This is an open question for which we can anticipate that a dynamically reconfigurable compensation cell, with much more complicated architecture than the one presented here, could solve the problem. In general, it will have to operate based on different mechanisms for tuning and athermalization e.g. electrical tuning plus thermo-optic compensation. Although a challenging task, it is feasible given the availability of specialty fibers and materials.

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