International Journal of Nanoelectronics and Materials
Volume 14 (Special Issue) December 2021 [317-323]

Reducing Inter-structural Gap on Serial In-line Mach-Zehnder Interferometer based on Fiber Micro-bottles

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ABSTRACT

In this paper, a systematic study of the effect of inter-structural gap between a series of in-line Mach-Zehnder interferometers (ILMZIs) is presented. Two similar ILMZIs, composed of a pair of fiber micro-bottles 3.5 cm apart, were fabricated and spliced in series by performing fusion splicing of a standard single-mode fiber using a commercial machine. The quality of the collective transmission spectrum of this serial formation is affected by the remnant cladding mode transmitted from preceding ILMZI. This study shows that there is a plain minimum structural gap of approximately 40 cm between the cascaded ILMIs to achieve a ripple-free resultant spectrum while retaining a broad free spectral range (FSR) of ~20 nm. It is also discovered that the minimum structural gap can be reduced by half or more before ripple began to deform by simply bending the connecting fiber for inducing sufficient loss to eliminate the remnant cladding mode, demonstrated with a curvature radius around 1.25 cm over only a short length of ~2.3 cm. This finding allows construction of a more compact architecture of serial ILMZIs based on fiber micro-bottles, with pristine interference spectrum, broad FSR and a high extinction ratio, which can be exploited as a new approach for spectrum shaping, multi-parameter sensing and wide dynamic range sensing.

Keywords: Mach-Zehnder interferometer, inter-structural gap, micro-bottles, spectrum shaping

1. INTRODUCTION

Nowadays, it is becoming increasingly popular with having a fiber optic sensor (FOS) compared to a conventional electrical sensor because of its advantageous features, such as non-electrical, small size and light weight. Among FOS, Mach-Zehnder interferometer (MZI) is a topic of research interest due to its sim[1]ple structure, low cost and wide applications especially in fiber sensors and communications [1-5]. The principle of MZI is based on coupling of between core and cladding modes, wherein cladding modes are excited to interfere with the core mode. There are many methods to excite cladding modes, for example, by changing the fibers diameter into a micro-bottle structure [6], down-taper structure [7], peanut structure [3] or core-offset [2] fiber which can be used to react with surrounding environment.

The cascading MZI structure with fiber Bragg grating (FBG) and long period grating (LPG) have been previously investigated and present good applications. Dong et al. [8] also presented a cascade of four up-tapered structures with a longer interferometer length and a narrow FSR, for curvature measurement by bending the middle point of the overall structure. Additionally, the cascaded MZIs have been reported in [6,9] that this arrangement can enhance the sensitivity of the structures compared to a single MZI structure. However, the architectural effect of these serial formations has not been fully studied and thus the control of spectral design cannot be established. Therefore, the sensing principles used in the reported papers are merely utilizing the collective spectrum that has a very limited free spectral range (FSR) of only a few nanometers wavelength, without having design control on the spectrum profile. In this paper, a systematic study of the effect of inter-structural gap between a series of in-line Mach-Zehnder

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interferometers (ILMZIs) based on fiber micro-bottles is presented. It is demonstrated that multiple ILMZIs with specifically designed spectra can be cascaded and thereafter produce a well-defined collective spectrum with broad FSR using a reduced inter-structural gap by applying a simple bending method.

2. WORKING PRINCIPLE

An ILMZI configuration requires coupling of light between core and cladding modes. The mechanism to provide the coupling can be achieved through a micro-bottle structure. The ILMZI has a disrupted waveguide structure in a form of micro-bottle section separated by a cavity length that causes some portion of propagation light to be no longer confined in the core region. Thus, after the first micro-bottle structure, there is evanescent waves related to some portion of light that is weakly guided in the cladding along the cavity length. The cavity length can provide a sensitive region for sensing due to expanded evanescent field for interaction with the ambient. At the second ILMZI structure, some of the cladding modes are re-coupled back into the remaining fundamental core mode by the micro-bottle region that contribute to the interference operation. In order to create a bulge on the optical fiber, an optical fusion splicer (Fujikura 62S+) was used to be operated in automatic mode, overlap of 150 μm, arc power of STD + 10 bit, arc time of 2000 ms, pre-fuse time of 400 ms and pre-fuse power was set standard. The separation distance between the micro-bottle structures defines the cavity length of the MZI. The schematic diagram of the proposed serial ILMZI structures with mode propagation in the cascaded MZIs is illustrated in Figure 1.

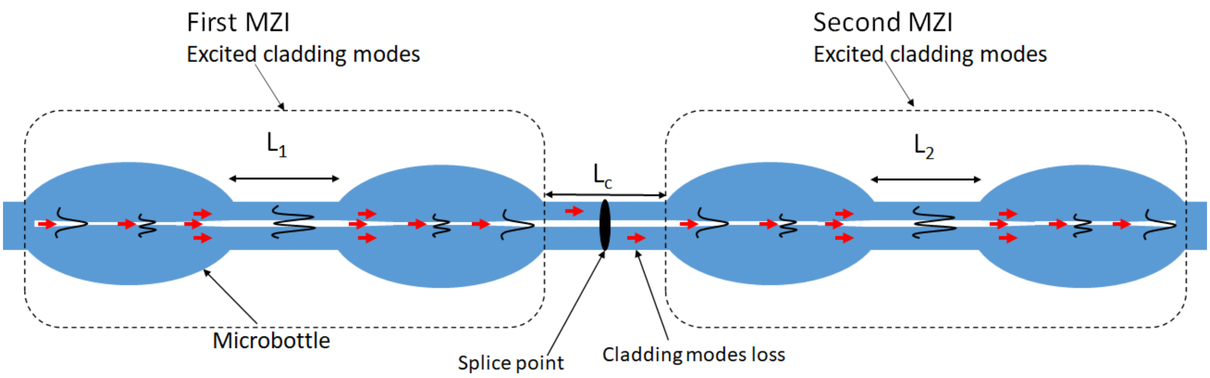

Figure 1. Structure of the serial ILMZI with modes propagation.

When there is an external perturbation and interaction with the ambient, for example change in temperature or strain, the peak power or peak wavelength variations could be observed in the transmission interference output. The temperature change will alter the properties of the MZI structure as the thermo-optic effect changes the effective refractive index, n_{eff}, by an amount of Δn_{eff}, while the thermo-elastic effect increases the effective length, L by an amount of ΔL, as given below [6]:

$$\frac{\Delta\lambda}{\lambda} = \left(\frac{\Delta L}{L} + \frac{\Delta n_{eff}}{n_{eff}}\right)\Delta T = (\alpha_{TEC} + \beta_{TOC})\Delta T \qquad (1)$$

where α_{TEC} is the thermal expansion coefficient, and β_{TOC} is the thermo-optic coefficient. When the cavity length is changed, strain, ε changes as:

$$\varepsilon = \frac{\Delta L}{L} \qquad (2)$$

and it also causes a phase difference, $\Delta\phi$, between the core mode, ϕ_{co}, and the cladding mode, ϕ_{cl} phases, which individually can be described as:

$$\phi_{co} = \frac{2\pi n_{co} L}{\lambda}, \phi_{cl} = \frac{2\pi n_{cl} L}{\lambda} \quad (3)$$

Generally, when there exists a change in the cavity length or effective refractive index in the core and cladding, it will contribute to the phase or spectral shift. This effect can either be enhanced or tailored by astutely cascading multiple ILMZIs that produces a new collective spectrum. In this paper, structural sensitivity will not be discussed, but instead it focuses on understanding the influence of structural gap between cascaded ILMZIs and finding a technique to attain pristine collective spectrum upon cascading multiple ILMZIs.

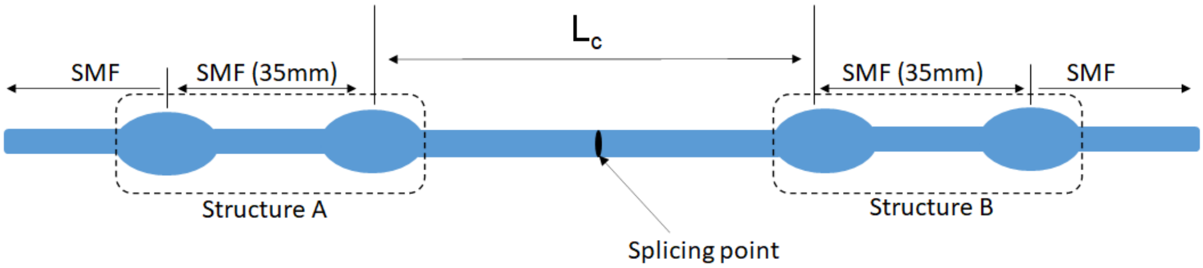

Figure 2. Illustration of serial ILMZI using micro-bottle structures.

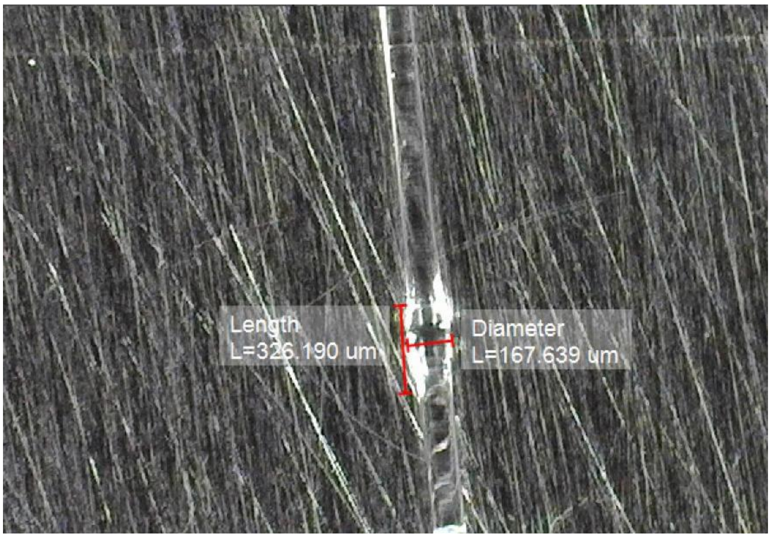

Figure 3. The microscope image of micro-bottle structure captured by Dino-Lite.

Each fabricated ILMZI structure consists of two fiber micro-bottles separated by a 35 mm cavity length. A serial ILMZI was then formed by splicing two or more ILMZIs on a commercial single mode fiber with the core and cladding diameters of 8 μm and 125 μm, respectively, NA of 0.14 and n_{eff} of 1.4679, as shown in Figure 2. The lengths for the connecting fiber, L_c, between two ILMZI under test are 40 cm, 20 cm, 5 cm and 4 cm. The proposed cascaded structure is expected to produce transmission spectra with well-defined interference fringes, a high extinction ratio and a broad FSR.

3. RESULTS AND DISCUSSION

Micro-bottle structures, each having dimensions of 167.639 μm diameter and 326.190 μm length as shown in Figure 3, were used in this experiment to form the ILMZIs that produce the desired interference spectrum. The individual spectrum of each ILMZI was first inspected and determined to match with the desired FSR. When two ILMZIs are spliced in a serial formation, the spectrum will be affected by remnant leaky cladding modes in the connecting fiber and result in ripples in the collective transmission spectrum at the output of the last ILMZI. On the contrary, absence of this remnant cladding modes that is weakly guided will then produce a pristine (i.e. ripple-free) collective spectrum. Before the two structures were joined through splicing process, the collective interference spectrum from joining the two structures using optical pigtails connector was recorded. Figure 4 shows the overlay of the individual spectrum of each ILMZI, marked as Structure A and Structure B (solid line), and collective spectrum obtained by connecting ILMZIs using optical pigtails connectors (dashed line) with long passive fiber around 2 m length. The reason of using a very long length of the connecting fiber is to ensure the remnant cladding mode totally disappear through propagation loss. The light in the fiber core will be continuing to propagate with minimum and negligible propagation loss. The interference spectrum that is transmitted from the preceding ILMZI to the next ILMZI is now free from any interfering cladding mode in the connecting fiber. Therefore, the collective transmission spectrum obtained by this long-length optical pigtail connectors was used as the reference in this experiment.

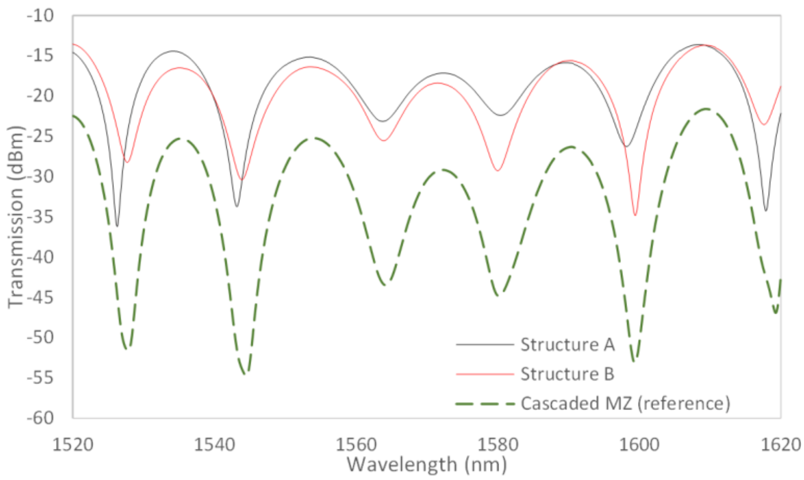

Figure 4. Individual spectrum of each ILMZI (solid line) with 35 mm cavity length and the reference collective spectrum of serial ILMZI with long optical pigtail connector (dashed line).

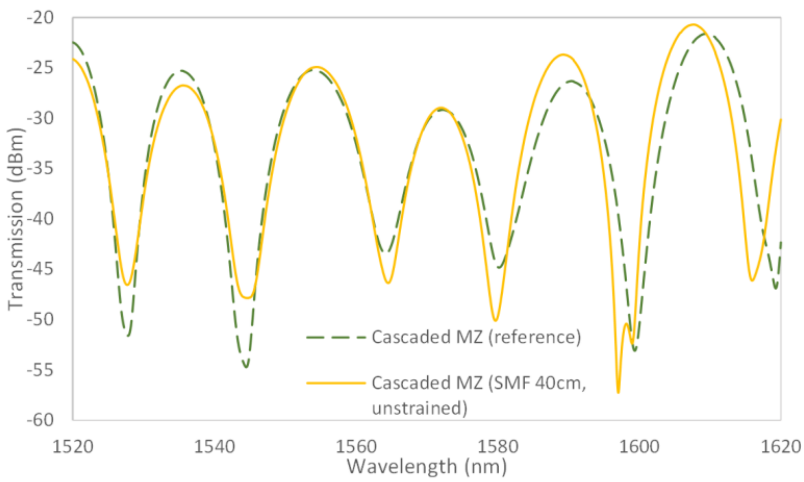

Figure 5. Overlay of collective transmission spectra of serial ILMZI (solid line) with connecting fiber length of 40 cm and the reference serial ILMZI with long optical pigtail connector (dashed line).

It was observed that there is a minimum connecting gap between two consecutive ILMZI before the spectrum begin to be disfigured with ripples. Figure 5 shows the spectrum as the L_c was set with a minimum length of 40 cm, just before any ripple starts to appear on the spectrum in idle state. The result shown a clean interference spectrum without any ripples because the output interference signal from the first ILMZI will remain confined in the core region, whereas the remnant cladding mode will be radiated away to the ambient along the length of the passive connecting fiber. Subsequently, the two ILMZIs were connected with various lengths of connecting fiber, L_c of 20, 5 and 4 cm.

When the L_c length was reduced to 20 cm, 5 cm and 4 cm, the ripples were clearly observed in the collective transmission spectrum. Figure 6(a) shows the collective transmission spectrum with ripples when the connecting fiber is in idle state. This effect happens because when the excited cladding mode was re-coupled back by the second micro-bottle in the first ILMZI, there is still a weakly guided remnant cladding mode remains in the connecting fiber.

On the other hand, when bending was applied on the connecting fiber, the collective transmission spectrum becomes noticeably smooth as shown in Figure 6(b). The required bending is performed only over a short length of around 2.3 cm with a curvature radius of 1.25 cm, as illustrated in Figure 7. These are roughly the optimum dimensions, which reasonably balance between the curvature size and the fragility of the fiber. The bending action expands the evanescent field outwards and rapidly radiate away into the ambient. The cladding mode thus become more lossy and this remaining leaky mode will be quickly diminished and reduced to zero. The collective transmission spectrum exhibits notably broad FSR of about 20 nm, which is useful for achieving high dynamic range in certain sensing applications.

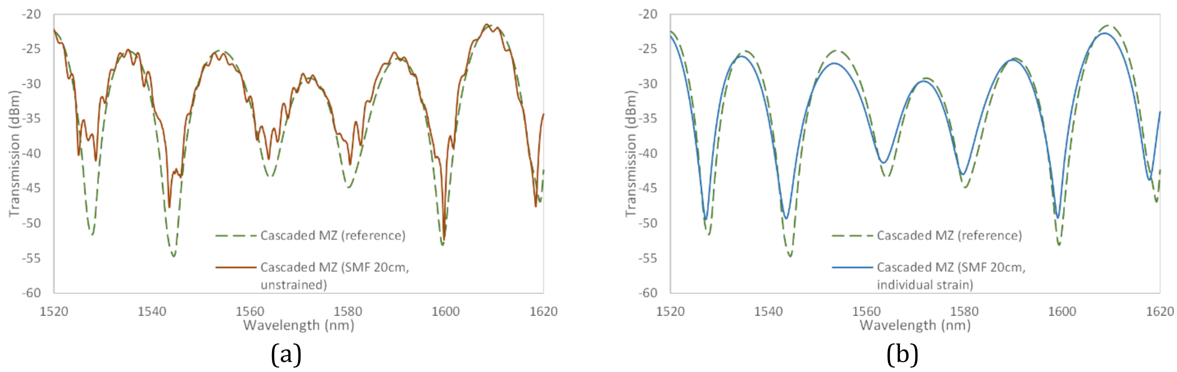

Figure 6. Collective transmission spectra of serial ILMZI (solid line) with connecting fiber length of 20 cm (a) without bending, and (b) with bending. The dashed line is the reference spectrum by the serial ILMZI with long optical pigtail connector.

However, the ripples started to become unpreventable when the L_c length reached 5 cm and 4 cm, even after bending is applied, as shown in Figure 8(a) and 8(b), respectively. The collective transmission spectrum is no longer the same as the reference spectrum. This is because the connecting fiber length is too short, wherein the remnant cladding mode could no longer be completely eliminated by the induced bending loss. Further attempt to induce higher bending loss will also introduce significant loss to the core mode, which is undesirable as it reduces the signal-to-noise ratio (SNR) of the collective signal.

The ripples cause the transmission spectrum to have chaotic profile and will practically define the FSR. These characteristics impose inconvenience to the sensing signal extraction and reduces measurement dynamic range. Moreover, the collective transmission spectrum becomes unpredictable and could not be designed as desired.

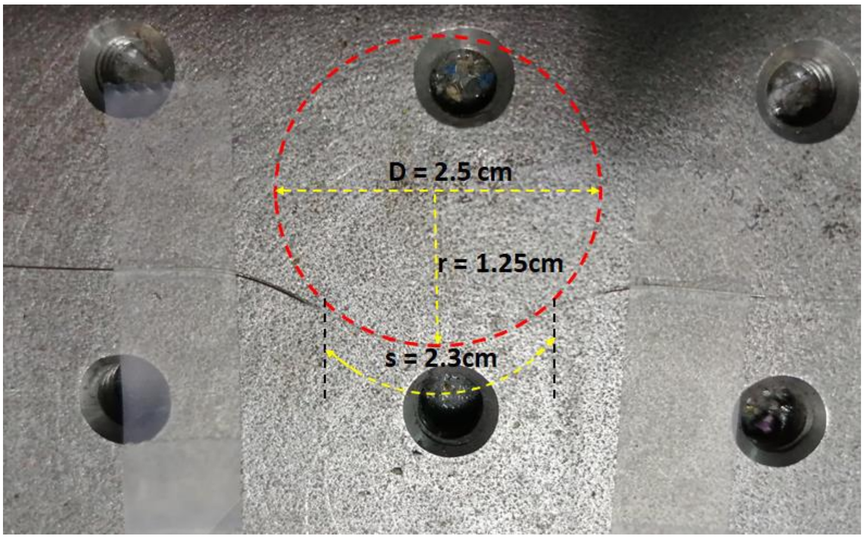

Figure 7. Connecting fiber under bending

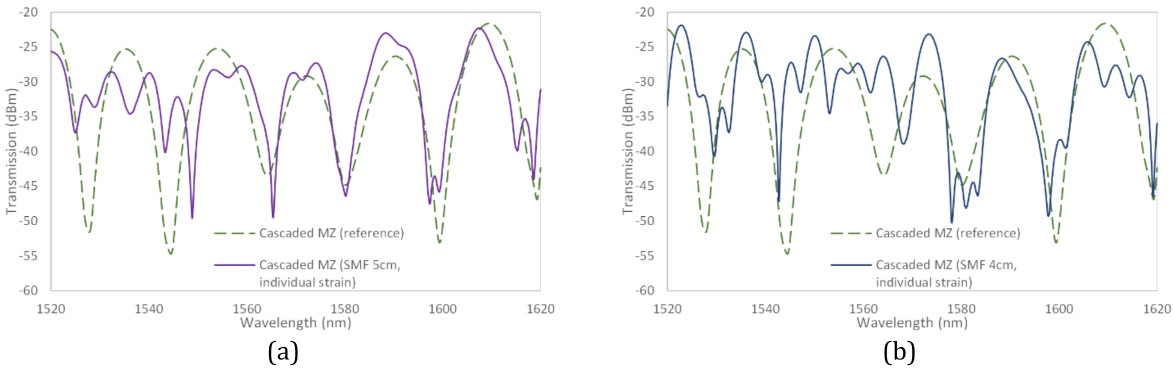

Figure 8. Collective transmission spectra of serial ILMZI (solid line) with connecting fiber length of (a) 5 *cm*, and (b) 4 *cm*. The dashed line is the reference spectrum by the serial ILMZI with long optical pigtail connector.

4. CONCLUSION

In conclusion, this paper presents a systematic study on the effect of structural gap in serial formation of ILMZI based on micro-bottles. Two similar and spectrally aligned ILMZIs were cascaded in series with various lengths of connecting fibers. The experiment results reveal that in order to retain broad FSR and pristine collective transmission spectrum, there must be a minimum connecting fiber length that must be able to eliminate the remnant cladding modes. It is also discovered and demonstrated that a simple bending could significantly reduce this minimum connecting fiber length by inducing bending loss to the weakly guided remnant cladding modes. This finding allows the control of the spectral design and produces well-defined collective transmission spectrum of a series of micro-bottle structures. Additionally, this approach allows a more compact serial micro-bottle structure to retain broad FSR, which is a desirable feature in many sensing applications.

ACKNOWLEDGEMENTS

The authors would like to express the gratitude to the members of the Fiber Optic Research Center (FORC) in Multimedia University (MMU). This work was supported by the TM Research Fund under Project RDTC/180009.

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