Optoelectronic oscillator with low temperature induced frequency drift

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Abstract: *We demonstrate a hollow-core photonic bandgap fiber delay-line based 10 GHz Optoelectronic oscillator (OEO) with over 6 times less temperature induced frequency drift compared to a standard single mode fiber delay-line based OEO.*

1. Introduction

Stable and spectrally pure microwave sources are essential in many applications in the fields of metrology, communication, signal processing, radar, radio astronomy, etc. These sources can be made using microwave electronics, however, when extremely low phase noise and high frequency (above 10 GHz) is needed, an optoelectronic oscillator (OEO) could be the best choice. An OEO is a microwave oscillator that contains an optical delay-line (e.g., optical fiber-based) in a feedback loop configuration [1]. The phase noise of the OEO-generated microwave signal can be reduced by increasing the delay in the OEO loop. Hence long lengths of fiber optic delay-line (100s of meters to several km) are used in OEOs to achieve low phase noise levels.

The use of long lengths of optical fiber, however, leads to a thermal drift of the generated OEO microwave signal frequency as the propagation time in optical fibers is susceptible to ambient temperature variations, causing associated variations in the OEO resonator length. It has been shown [2] that for fused silica, the contribution to the Temperature Coefficient of Delay (TCD) from the change of refractive index is 37 ps/km/K and the contribution from the change of length is 2 ps/km/K. The net resulting TCD of 39 ps/km/K is consistent with the experimental results measured for standard single mode fibers (SMF) such as SMF-28 [3].

This thermal sensitivity can be greatly reduced when using optical fibers in which the light is guided through air. For example, in Hollow-Core Photonic Bandgap Fibers (HC-PBGFs) more than 99.8% [4] of the light can be guided in air. Since the thermo-optic coefficient of air (at constant air volume) is negligible, the TCD in HC-PBGF is mainly determined by the temperature induced length variations rather than by the refractive index changes. In [2] we reported measured TCD values of 37.4 ps/km/K for SMF and 2 ps/km/K for HC-PBGF. Hence the utilization of HC-PBGF delay-lines is expected to result in a significant reduction in OEO frequency drift due to temperature variations. This was investigated in [5], however, the demonstration was limited to a very short length of HC-PBGF that was incompatible with the generation of low-noise microwave signals.

Here we use an 860 m long all-HC-PBGF delay-line in a 10 GHz OEO and characterize the device in terms of the temperature-induced frequency drift and compare it to an SMF-based OEO. To the best of our knowledge, this is the first time a practical length of HC-PBGF have been used as a delay-line in an OEO cavity.

2. Experimental setup and frequency drift measurements

Fig. 1a shows our OEO setup, which employed a single fiber-based delay-line. The HC-PBGF (fig. 1b) had a length of 860 m and was a 19-cell core design (core diameter of 29.5 μm) with a minimum loss of ~8 dB/km. The fiber induced a delay of 2.9 μs (its group index is ~1). It was spliced with SMF pigtails, which resulted in an overall loss of 16 dB. This could be significantly reduced with improved splicing procedure [6]. To compensate for the large splicing loss, an Erbium-doped fiber amplifier (EDFA) was placed in front of the fiber. For comparison, we used an OEO with a SMF which provided a similar delay (500 m of SMF, creating a delay of ~2.5 μs) to the HC-PBGF. We cascaded it with an attenuator to create comparable net loss to that of the HC-PBGF. Both fibers were spooled on ~16 cm diameter fibre spools (Fig. 1b). The $LiNbO_3$ Mach-Zehnder modulator bias was kept at quadrature using a feedback loop, as the bias point drift would cause frequency drift in the OEO. The OEO frequency drift was monitored by comparing it with a reference signal derived from an optical frequency comb (Menlo Systems GmbH) that was locked to a GPS (Global positioning system) signal.

First, the OEO was tested when exposing the entire OEO setup (delay-line, optical and microwave components) to the ambient temperature. Due to the laboratory air conditioning unit switching on and off, we observed ±1 °C periodic variations in the temperature, Fig. 1c (upper panel). The measured OEO frequency variations associated with this were 120 kHz with the SMF and 18 kHz with the HC-PBGF (Fig. 1c) which represents a factor of 6.7 improvement with HC-PBGF as compared to SMF.

To characterize the impact of the temperature sensitivity of the fiber delay-lines in isolation, we placed them inside an oven and covered the rest of the OEO with foam to thermally shield it from the ambient temperature variations (as shown in Fig. 1a). During the experiment, the temperature of the fiber delay-line spools was increased by 9 °C and the frequency drift of the OEO was monitored, Fig. 1d.

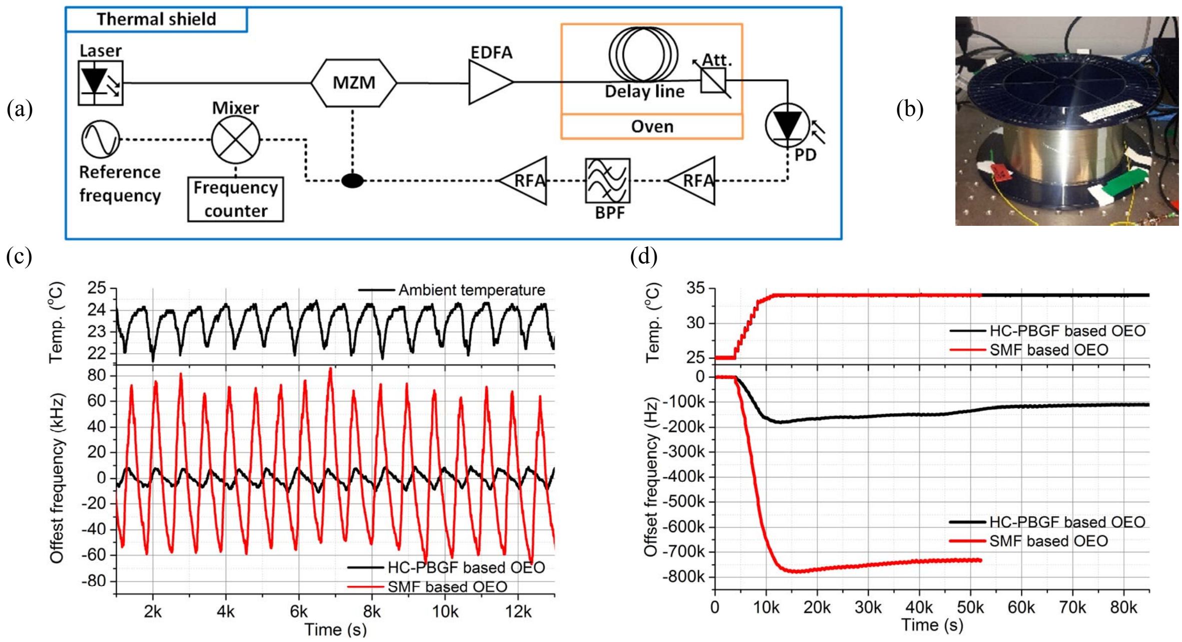

Figure 1. (a) Schematic diagram of the experimental setup. MZM: Mach Zehnder Modulator, PD: Photodetector, RFA: microwave amplifier, EDFA: Erbium-doped fiber amplifier, Att.: Attenuator, BPF: Band-pass filter, (b) 860 m HC-PBGF sample spool (c) Frequency drift of the OEO at ambient room temperature that periodically varied by about ±1 °C (d) Frequency drift of the OEO when the temperature of the fiber spool delay-lines was increased by 9 °C (delay-line temperature shown in the upper panel; the rest of the setup was shielded).

With SMF and HC-PBGF, the OEO experienced 730 kHz and 110 kHz frequency drifts, respectively (Fig. 1d). Since the delay per unit length is different in the two fiber samples (3 µs/km in HC-PBGF and 5 µs/km in SMF), the frequency drift per unit delay (rather than unit length) was used for evaluation of the delay-line fiber samples performance. The frequency drift per unit delay was calculated to be 3.0×10^{11} Hz/s for SMF and 3.8×10^{10} Hz/s for HC-PBGF, showing that the HC-PBGF-based delay-line was 7.9 times less sensitive to temperature than the SMF.

Next we calculated the TCDs of the two fiber samples by calculating the change in the free spectral range (and in return the change of delay) in the OEO cavity due to the temperature change [7]. The RF mode spacing of the OEO with the SMF and HC-PBGF was 365 kHz and 320 kHz, respectively. The calculated values of 44.4 ps/km/K and 4.4 ps/km/K for SMF and HC-PBGF respectively are slightly higher than those previously-reported (39 ps/km/K for SMF and 2 ps/km/K for HC-PBGF). We plan to investigate the causes responsible for this discrepancy.

3. Conclusions

We demonstrated an 860 m long HC-PBGF delay-line based 10 GHz OEO. Under ambient temperature conditions, without any (thermal) shielding, the HC-PBGF delay-line based OEO showed 6.7 times smaller sensitivity of its oscillating frequency as compared to a SMF delay-line based OEO. We have also shown that the temperature stability improvement from the delay-line itself is almost 8 times.

4. References

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