Hollow Core Fibre based Fabry-Perot Resonators with Q Factor Over 90 billion

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***Summary*—Q factor over 90 billion is demonstrated for the first time in hollow core fibre based Fabry-Perot resonators. This is achieved thanks to low-loss of the latest hollow core fibers. Such high Q factor together with other beneficial properties of hollow core fibers such as low thermal sensitivity and high power handling is of interest for a range of applications including laser stabilization in metrology.**

Keywords—Laser locking; Fabry-Perot, resonator

I. Introduction

Low phase noise lasers with high carrier stability are of interest in applications such as atomic clocks [1], microwave photonics [2], and gravitational wave detectors [3]. The best performance has been achieved via laser locking to an external frequency reference using the Pound–Drever–Hall method. These frequency references include optical delay lines [4], whispering-gallery-mode resonators (WGM) [5] and Fabry-Perot (FP) resonators/cavities [6]. Besides stability of the frequency reference itself, the performance of the locked laser strongly depends on the spectral width of the frequency reference resonance feature to which the laser is locked. This is because the SNR of the frequency discrimination of the laser noise against other noise sources such as photodetector noise, shot noise, and electronic noise is inversely proportional to this resonance feature spectral width [7]. The resonance feature spectral width is typically inversely proportional to the delay introduced by the optical frequency reference. It is typically characterized by a Q factor defined as the full width at half of maximum (FWHM) of the resonance feature spectral width divided by the carrier frequency. In optical fiber delay lines, light passes through the fiber only once (e.g., in a Mach-Zehnder configuration) or twice (e.g., in Michelson configuration), requiring long fiber lengths to achieve high Q. Light can propagate many times through WGM and FP resonators (this is characterized by their finesse), enabling high Q factor for high-finesse resonators. In WGM resonators that are typically made of calcium fluoride [5] and silicon, high finesse requires the incident optical power to be low enough to avoid nonlinear effects. This in turn reduces the SNR of the signal, which is detrimental to the locked laser performance. Additionally, the interaction between glass and light in WGM resonators makes it susceptible to temperature fluctuations due to thermo-optic effect. The same shortcoming is witnessed by fiber optic delay lines in which light propagates through silica glass. The interaction with the solid material is strongly suppressed in FP cavities in which light typically travels in the vacuum. As the cavity length is limited by practical constraints (typically to 10 cm, with cavities up to 50 cm reported in the literature [8]), high Q of > 170 billion is achieved only when finesse is very high (>100 000 [8]), requiring accurate alignment and high-quality mirrors. Operation of the entire FP cavity in vacuum also makes the system relatively bulky.

Fiber delay line environmental stability has been improved by over an order of magnitude by propagating light through a hollow core rather than silica glass in the newly-emerging hollow core fiber (HCFs) [9]. Length of HCF required for achieving high Q can be greatly reduced (to reduce the weight) by forming an FP resonator in which

$$Q = \frac{2n_g \cdot F \cdot L}{\lambda} \tag{1}$$

where F is the finesse, L resonator length, n_g group index of the transmission media and λ operating wavelength. As HCF-FP can be significantly longer than bulk FP optical cavity, high Q can be obtained even for moderate values of finesse. Finesse of HCF-FP can reach up to 5 000 [10], although the attenuation of HCF poses a limitation in the length that can be used before the finesse starts dropping and thus reducing the Q.

Here, we demonstrate that by using the latest generation double nested antiresonant nodeless HCF (DNANF) with a record-low loss of 0.174 dB/km [11], we can achieve HCF-FP with Q value of over 90 billion. The new HCF-FP with such a high Q value, together with its high nonlinear threshold and thermal stability, will be a strong candidate for frequency reference used in laser stabilization.

II. Exprriments/results

The HCF-FP schematics is shown in Fig. 1. The HCF is the latest generation of DNANF with a loss of 0.174 dB/km [11], the cross-section of which is shown as inset in Fig. 1. The low loss is crucial as it enables high finesse in a long-length HCF-FP resonator. Both fiber ends were put onto 3-axes micro-positioning stages. The transmissivity of the two cavity mirrors was measured to be -32.6 dB (0.055%) and -31.1 dB (0.078%). The two mirrors were mounted on tilt and yaw mounts and put close to the HCF end faces.

Light was launched into the FP from standard single mode fibre (SSMF) using a pair of lenses with their focal length ratio chosen for efficient coupling from SSMF (mode field diameter (MFD) of 10.4 µm) to HCF (MFD of 24 µm). At the HCF-FP output, identical optics was used to couple light back into the SSMF.

The measurement setup is the same as described in [10]. We measure the finesse and the free spectral range (FSR) through RF beating signal of the transmitted signal and calculate Q as:

$$Q = \frac{\nu \cdot F}{FSR} \quad (2)$$

where ν is the optical frequency of the incident light.

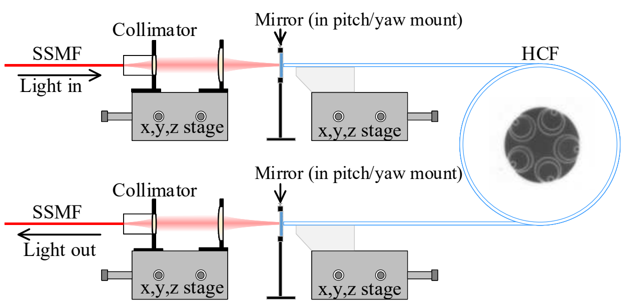

Fig. 1 HCF-FP resonator with light coupling to and from an SSMF. HCF microstructure SEM image is shown in inset.

We made two samples with a length of 25 m and 250 m, respectively. The RF spectrum of the 250-m sample is shown in Fig. 2. The measured RF spectrum was fitted by the system transfer function (Eq. (1) in [10]). For the 250-m sample, we measured a finesse and FSR of 280 and 590 kHz at 1550 nm, leading to a Q value of 9.2×10^{10}.

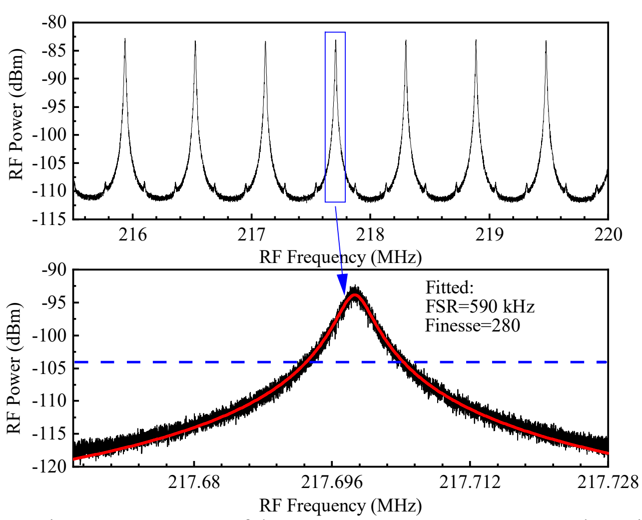

Fig. 2 RF spectrum of the 250 m HCF-FP resonator together with its detail around one transmission peak.

We then measured the Q factor of the two samples across the C band, as shown in Fig. 3. For the 250-m sample, the Q factors were $9\pm0.5\times10^{10}$ and for the 25-m sample, the Q factors were around $5.5\pm0.1\times10^{10}$. The Q factor here is comparable to bulk-optical FP resonator used in [6] and about 100 times larger than the WGM resonator used in [5]. We believe that this ultrahigh Q factor will make it a strong candidate as a frequency reference used in stabilized lasers.

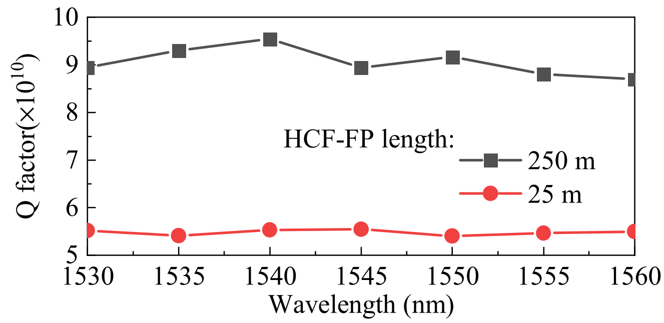

Fig. 3 Q factor of the 250-m and 25-m HCF-FP resonators.

III. Conclusions

By using the latest generation of hollow core fibre: double nested antiresonant fibre, we demonstrated hollow core fibre based Fabry-Perot resonators with Q factor value of 90 billion cross the entire telecom C-band. Such value is about 100 times larger than in the WGM resonator used in [5] and as far as we know represents the highest value achieved in fibre cavities. The Q factor value is comparable to bulk-optic FP cavities [6] while being more lightweight, compact, robust, and insensitive to misalignment during operation. We believe that such a FP resonator can be a useful tool in laser stabilization.

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