Direct Measurement of Resonant Phonon Modes in Optical Fibers

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Abstract: We probe and model phonon modes in optical fibre by means of frequency noise measurements of distributed-feedback fibre lasers. Resonant acoustic waves with femtometer-scale amplitudes are fully characterised as they interact with the optical cavity. © 2023 The Author(s)

1. Introduction

Distributed feedback (DFB) fibre lasers are known for their low noise properties which can be used to make high-performance single frequency fibre lasers (SFFL). Applications of SFFLs range from atomic sensors [1] to optical fibre sensing [2] and rely on exceptionally low frequency noise. Possible sources of frequency noise include environmental disturbances, mechanical vibrations, electronic noise, and pump and amplifier noise. Reduction of the frequency noise of DFB lasers is therefore crucial to preserve spectral purity and minimise linewidth broadening, and has been achieved by minimising the pump relative intensity noise (RIN) [3], engineering of the laser substrate [4], and locking to fibre cavities and delay lines [5].

In this contribution, we investigate an additional source of noise that has been overlooked so far, namely the formation of standing acoustic waves within the optical fibre. These acoustic waves interact with the Fibre Bragg Grating (FBG) forming the DFB optical cavity and influence the frequency noise of the laser by causing a periodic modulation of the grating. While acoustic waves have been measured before in optical fibres either in the form of Brillouin scattering [6] or by externally driving mechanical oscillations [7], to the best of our knowledge, there have been no reported studies of resonant phonon modes affecting the frequency of a laser. In the following, we present the first reported characterisation of thermally excited resonant acoustic waves on optical fibres with envelope amplitudes in the femtometer scale.

2. Experimental results and discussion

Standing acoustic waves as source of frequency noise in a SFFL has been studied by creating a mechanical cavity around the FBG of a Tm-doped DFB laser. The fibre laser has two contact points with the substrate between which a standing acoustic wave can resonate. While the resonant acoustic waves in the cavity do not appear to be generated by any optical process, they can still be detected by measuring the effect that the vibrations in the fibre have on the linewidth of a DFB fibre laser. This is in turn quantified by measuring the frequency noise spectrum of the laser with an unbalanced fibre-based Michelson interferometer (MI), as shown in the schematic in Fig. 1. A cavity of length d (corresponding to the fibre separation between the laser contact points) will support resonant waves with a free spectral range (FSR) given by:

$$\Delta\nu_{\mathrm{FSR}} = n \cdot \frac{c_w}{2d}, \tag{1}$$

where $n = 1, 2, \ldots$ is the mode number and c_w is the velocity of the wave in the medium. Simulating the mechanical system with COMSOL yielded all possible vibrational eigenmodes of a coated silica fibre of finite length. These consists of the trivial vibrating string mode, a twist mode with velocity $c_w = 1563$ m/s and a radial mode with velocity $c_w = 3833$ m/s. Stylised fibre cross-sections of the radial and twist modes are shown in Fig. 1 together with the FSR corresponding to the simulated wave velocities. Extensive experiments have been carried out to exclude any other possible explanation of the acoustic waves.

Frequency noise spectra measured with the MI are shown in Fig. 2 for a laser glued on a substrate (separation $d = 62$ mm) and for two "free standing" lasers with either no contact points or a distance $d = 30$ cm

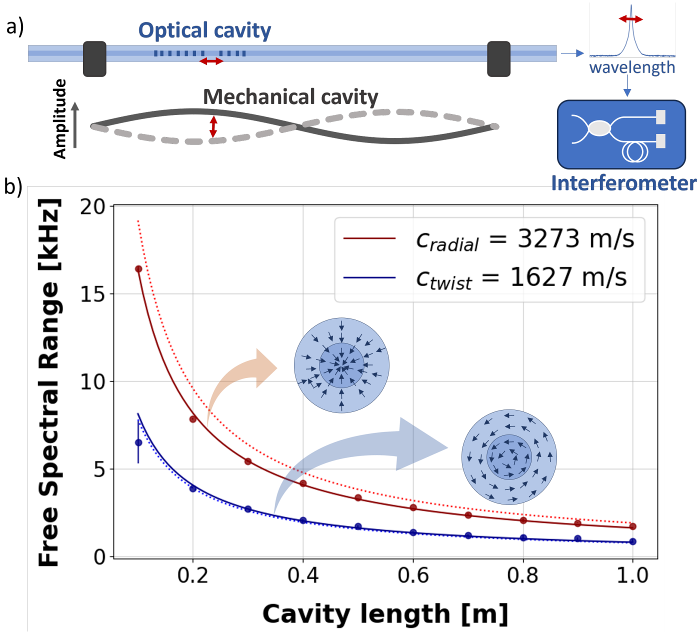

Fig. 1. a) Schematic of the experimental set-up illustrating how a resonant mechanical wave in the cavity formed by the contact points affects the FBG of the DFB laser. The interplay between mechanical and optical cavities is measured through the frequency noise of the laser via a Michelson interferometer. b) FSR of the phonon modes as a function of cavity length. The insets show a simplified graphic of the fibre cross-section for the two different modes sustained by the cavity. The dashed lines show the simulated wave velocities of $c_{twist} = 1652$ and $c_{radial} = 3833\,$m/s, while the solid line is the value for c_w obtained by fitting experimental data (points) with Eq. 1.

between the contact points. Unmounted fibre lasers show a worse frequency noise behaviour compared to the substrate-mounted ones due to increased thermal effects and worsened overall stability. However, the removal of the substrate allowed us to easily change the relative position of the contact points and the distance d between them. It is clear that perturbing the fibre around the DFB FBG cavity has an influence on the frequency noise of the laser, and that this effect depends on the distance d between the fibre contact points. The appearance of repetitive, equidistant peaks in the frequency noise spectra suggest a resonant nature of this phenomenon, with a mechanical cavity being created on the fibre by the contact points. The amplitude of the resonant waves in this cavity can in turn be probed along the cavity axis by varying the position of the laser FBG relative to the contact points on the fibre. Indeed, if we keep the cavity length constant at 30 cm and we consider the relative amplitude of each peak when the DFB FBG is moved across the mechanical cavity, we can map the evolution of the waves amplitude along the cavity axis for the fundamental mode and the first five harmonics. Each peak in the frequency noise plot corresponds to a resonant mode in the cavity, whose amplitude correlates with the amplitude of the standing acoustic wave in the fibre. It is known that the amplitude of a standing wave can be described in the steady state by $y(x) = y_{\max} \sin\left(\frac{2\pi x}{\lambda}\right)$, where $\lambda = \frac{2d}{n}$ is the wavelength. The strain on the optical fibre is phase shifted by $\pi/2$ compared to the amplitude of the acoustic waves. A full 3D COMSOL simulation further confirms the shape of the waves and the relationship between strain on the fibre and amplitude of the waves.

We note from Eq. 1 that we can derive the speed of a wave travelling in a mechanical cavity on the fibre by changing d and measuring $\Delta\nu_{\mathrm{FSR}}$. The free spectral range $\Delta\nu_{\mathrm{FSR}}$ corresponds to the spacing between the peaks in the frequency noise spectra, and, due to the periodicity of the signal, can be obtained by calculating the power spectral density (PSD) of the frequency noise. This results in a PSD density spectrum with two main peaks corresponding to the FSR of the two resonant modes. The FSR frequencies have been plotted versus the cavity length in Fig. 1. Fitting the data with Eq. 1 allows us to obtain the wave velocity for the twist and the radial modes. This gives values for $c_{radial} = 3273\,$m/s and $c_{twist} = 1627\,$m/s, which are within 10% of the simulation results. This discrepancy is due to the precise fibre coating material being unknown, thus resulting in different material parameters in the simulation compared to the experiment. Knowing the material properties of the coating is crucial for a accurate simulation since, as we can see from the simulated cross sections of Fig. 1, the wave mostly travels in the coating of the fibre. Having a softer coating thus

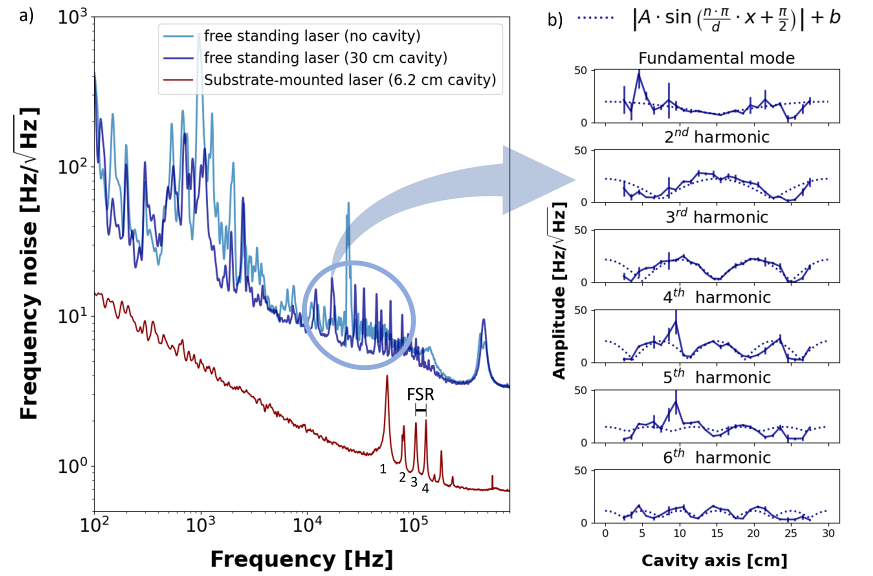

Fig. 2. a)Frequency noise of Tm-doped DFB fibre lasers. The spectrum changes significantly depending on whether the laser is attached on a substrate or is run as a free standing fibre. b) Amplitude of the first six peaks in frequency noise spectrum versus the position of the FBG in the cavity ($d = 30\,\text{cm}$). The dotted line shows a fit with the absolute value of a sin function.

dampens the vibrational modes, while a harder coating exacerbate their effect. Heating the fibre above the glass transition temperature of the coating polymer material greatly reduced the amplitude of the peaks in the frequency noise spectra, and the same effect can been achieved by surrounding the fibre with a more viscous material.

At last, to get a sense of magnitude of the local strain on the FBG, we need to consider the actual variation in the laser frequency that is measured in the frequency noise spectra. The frequency variation due to the acoustic waves can in turn be related to the strain felt by the FBG via the strain-optic coefficient. The longitudinal strain on the fibre is then converted to radial displacement with the Poisson ratio of silica, giving an estimate for the amplitude of the acoustic waves of ~ 1 fm.

3. Conclusion

This work presents a first-of-its-kind measurement of phonon modes in optical fibres. By leveraging the extreme sensitivity to frequency noise of DFB SFFLs, it is possible to measure thermally driven resonant acoustic waves with amplitudes in the femtometers range. Accurate measurements and careful data analysis allowed us to probe and characterise new types of acoustic waves on optical fibres, with supporting theories confirmed by finite elements simulations. While we propose a possible method to attenuate this effect in light of improving frequency noise performances of fibre lasers, we also note that the same principles could be applied to a new generation of resonant fibre pressure sensors.

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