Microfibre pulling and coupling to whispering-gallery mode resonators

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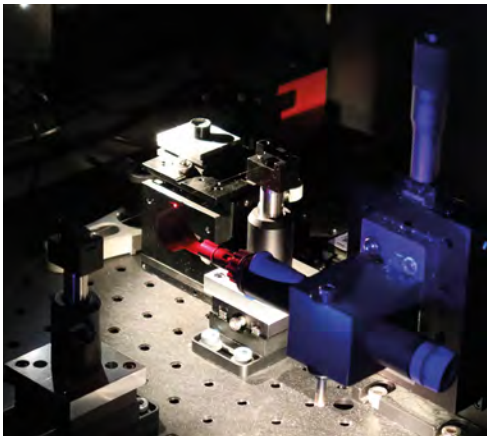

Whispering-gallery mode resonators have become a basic brick of modern photonics, thanks to their extremely narrow resonances. The resulting enhanced light-matter interaction can be leveraged in a variety of applications, from biological sensors to clocks and optical telecommunications. This labwork has been developped to allow Master 2 students to manipulate these resonators, as well as to illustrate wave-optics concepts seen during lectures: propagating modes, evanescent coupling, resonances and interferences.

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The progress of nanophotonics in the past few decades has impacted a large variety of applications, ranging from sensors and spectroscopy to optical telecommunications, time and frequency metrology and neuro-morphic computing. This fast-paced development and its ubiquity is such that most master's degrees in optics now include at least one lecture on the peculiarities of photonics at the nanoscale level. New wave-optics concepts are introduced at this stage: propagation modes, near-field optics, and evanescent coupling [1], which complement bachelor's level notions of interference, resonance, polarisation, and diffraction. While a large choice of experiments is available for labworks on the latter, the practical discovery of light-matter interactions at the nanoscale level remains challenging, with only a few readily available solutions. Nanophotonics samples are indeed hardly commercially available, custom fabrication in clean-room facility is prohibitively expensive, micro-manipulation and optical characterization require specialized equipment. At the University of Bourgogne, we took up this challenge by using standard telecom equipment – single-mode fibres, splicer, photodiode – and a little bit of handiwork to come up with a labwork on the evanescent coupling between a microfibre and a silica micro-sphere, both components being made by students. Along the way, we teach how to manipulate optical fibres, lasers, and photodiodes, we observe interferences between co-propagating modes, we evanescently couple light from the fibre to the whispering-gallery mode resonator, and we measure the resonances' linewidths to evaluate their quality-factors.

Whispering-gallery mode resonators and evanescent coupling

Whispering-gallery modes (WGM) are a particular type of propagation modes that form around a concave surface, typically a sphere or a toroid. Historically, WGM were first observed with acoustic waves in the dome of St Paul's Cathedral in London by Lord Rayleigh in 1910: a whisper softly spoken on the edge of the dome could be heard at any point on the circumference of the dome, as the walls reflect and refocus the sound waves,

thus allowing for propagation with exceptionally low attenuation. In the same paper, Lord Rayleigh suggests that one could perform the same operation with electromagnetic waves within a dielectric material of appropriate shape [2].
Conveniently, the guiding properties of WGM can be intuitively understood using ray optics: let us consider a light ray propagating within a dielectric material of index $n > 1$ surrounded by air. Snell's law states that if the angle of incidence is greater than $\arcsin\left(\frac{1}{n}\right)$, the incoming ray light is totally reflected. By giving an appropriate shape to the dielectric material, such as a sphere for instance, these light rays end up coming back to their initial point, and therefore follow a closed path trajectory within the material. At this stage, students may remember their past lectures on interferences and resonators: if an optical wave overlaps with a delayed version of itself, a constructive interference can occur provided the optical path difference corresponds to an integer number of wavelengths. The total internal reflections at the boundary ensure that light is undergoing many round trips, hence leading to N-wave interferences, or *resonances*. For a complete description of the WGM resonator, wave-optics is mandatory and shows that several spatial modes can be excited within the device, as shown in Fig 1a. These modes all have different distributions of the electromagnetic field, different effective indices, and therefore different resonance wavelengths and free spectral ranges. One tricky question regarding the use of WGM resonators is how to inject light into them in a way compatible with total internal reflexion: directly shining a glass sphere with a laser beam will, unfortunately, not excite any WGM efficiently. One convenient solution makes use of an optical microfibre: it consists of a simple rod of dielectric whose diameter is of the same order of magnitude as the wavelength. With such a small diameter, light is strongly confined into the waveguide, to such an extent that the electromagnetic field extends outside in air, in the form of an *evanescent wave*. This behaviour is shown in Fig 1b for two different propagation modes, the fundamental one, HE_{11}, and a higher order mode with similar symmetry, HE_{12}. In a similar fashion, WGM also present an evanescent component outside the material, as can be seen with a keen eye on Fig. 1a.
The interaction of two different propagative modes through their respective evanescent fields allow the coupling between each other: this is called *evanescent coupling*. Launching light to a WGM resonator therefore simply consists in bringing it in contact with a microfibre in which light propagates, provided that the microfibre is sufficiently thin so that the evanescent field extends far enough. For the telecommunication wavelength at 1.55 µm and a silica microfibre, calculations show that a diameter between 1 and 3 µm yields enough evanescent field.

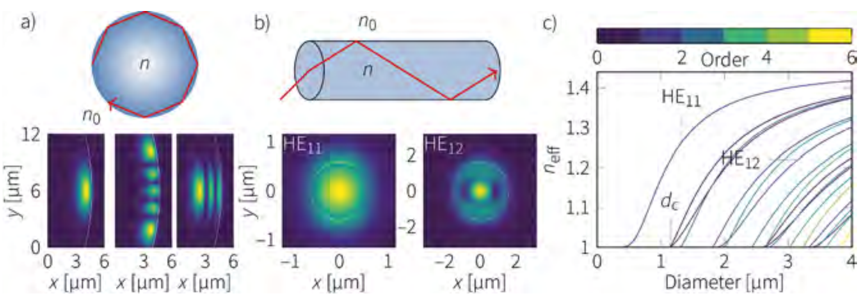
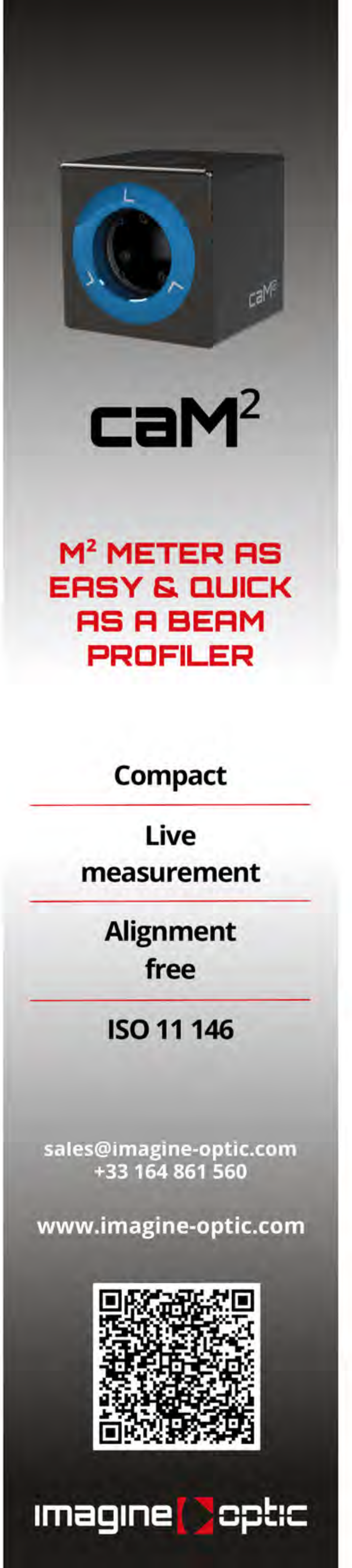


Figure 1. a) Scheme of a WGM resonator, as seen from the ray optics point of view (top). In the wave-optics description (bottom), several spatial modes can be excited. b) Scheme of a microfibre, which consists of a plain rod of dielectric material. Guiding can be understood as a series of total internal reflections (top) or as propagating modes (bottom). The HE_{11} (fundamental) and HE_{12} modes have been chosen because they share the same symmetry and will be of particular interest in the following sections. c) Effective indices of the propagation modes inside a silica microfibre of varying diameters.



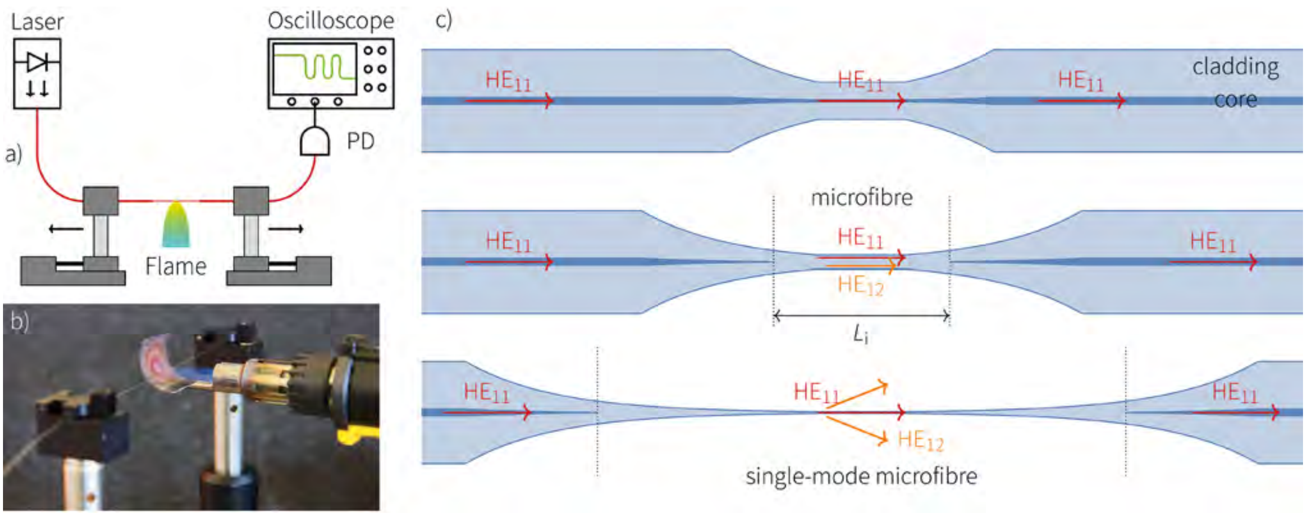


Figure 2. a) Scheme of the experimental setup for fabricating a microfibre from a single-mode silica fibre. b) Photograph of the fibre being heated by the blowtorch and stretched by the motorized translation stages. c) Principle of the observed modal interferences: when the fibre drawing starts, the guiding is done by the core-cladding interface, therefore in the fundamental mode. After a longer pulling duration, the guiding is performed by the air-glass interface, in a multi-mode configuration. At the end of the fabrication, higher order modes are scattered away from the fibre.

Microfibre fabrication

A convenient way to fabricate a microfibre is to start from a silica single-mode fibre, heat it with a blowtorch and pull it on both sides with synchronized motors (see Fig 2 a and b). This so-called flame-brushing technique [4] requires a relatively steady flame with a temperature greater than 1200°C, the glass transition temperature of silica. In practice, a cheap butane gas-powered soldering iron gets the job done appropriately. The movement of the two motors must be slow enough to let the fibre heat up to its glass transition temperature, but not too much for the gaz of the blowtorch not to blow away the microfibre. To ensure that these conditions are met from start to finish of the fibre pulling, we move the motors with a constant acceleration of 0.005 mm.s^{-2} on both ends.

To obtain the desired microfibre, we need a way to evaluate its minimum diameter to stop the pulling at the right moment. An elegant and efficient way to achieve this makes use of the waveguiding properties of fibres and microfibres, and their dependency with the diameter. If laser light is sent into a single-mode fibre, the wave is guided by the interface between the core and the cladding in the fibre's unique fundamental mode, HE_{11}. When we start stretching the fibre, the core and cladding both see their diameters reduced, and the guiding remains single-mode for a while. However, once the core diameter becomes smaller than the wavelength, the core-cladding boundary can no longer guide light, and it's the cladding-air interface — or more accurately glass-air interface — that becomes the waveguide: we have formed a microfibre. This change of waveguiding conditions occurs when the glass rod diameter is typically around 10 µm, and is therefore extremely multimode, as one can extrapolate from Fig. 1 c). The input light in the HE_{11} mode of the single-mode fibre can only couple to the microfibre modes of similar symmetry and, in practice, the HE_{11} mode of the microfibre receives most of the optical power, and the HE_{12}, first higher-order mode with a similar symmetry, gets most of the remaining signal. Only occasionally, when dust is present, or the fibre is not properly aligned with the flame, other modes can be coupled. Once populated, the two (or more) modes propagate independently towards the output of the microfibre, where they combine back together in the core of the single-mode fibre. Since HE_{11} and HE_{12} have different effective indices, an *interference* is produced, and the intensity at the output of the fibre can be approximated by:

$$I(L_i) = I_0\left(1 + C\cos\left(\frac{2\pi}{\lambda}L_i(n_{11} - n_{12})\right)\right)$$

where L_i is the microfibre length, I_0 the input intensity, C the contrast factor, λ the wavelength and n_{11} and n_{12} are the effective indices of the HE_{11} and HE_{12} modes, respectively. During the pulling process, the interference length L_i increases, and the optical intensity oscillates, providing information on the effective indices difference. More importantly, when the diameter of the microfibre decreases below the *critical diameter* d_c, the higher order modes are becoming leaky and the interferences are vanishing at the output of the fibre. Using this feature as a criterion for stopping the fibre pulling when the microfibre becomes single-mode, we stop both motors and the blowtorch as soon as the modal interferences disappear on the monitor. The principle of the evolution of these modal interferences during the microfibre fabrication process is summed up in Fig. 2c.

Once these principles have been explained, the implementation of the experiment can be taken care of by the students: connect the laser to the fibre, strip a few centimetres of polymer coating from the fibre, so that the flame only heat glass, cleave the output fibre and align it with the photodetector. Once ready, the blowtorch can be lit up and the motors started, while the photodetector signal is recorded on an oscilloscope. A typical recording is presented in Fig. 3a: the intensity is constant at first, showing that light propagates in the core of the fibre. Then, the modal interferences appear as the core becomes smaller than the wavelength and light is guided by the multimode glass-air interface. Finally, the interferences suddenly disappear, as the microfibre becomes single-mode, with a minimum diameter close to d_c.

The transmitted signal is further analysed to foster discussions on the modal interferences by calculating its spectrogram. The evolution of the frequency components during the fibre drawing appears clearly, as shown in Fig. 3b). The most striking feature is the appearance of a strong component at around 40 seconds, whose frequency increases rapidly up to 160 Hz, before slightly diminishing and then vanishing. This component most likely belongs to the interference between HE_{11} and HE_{12} modes, as they are the most excited modes. The interference frequency increases both due to the acceleration of the motors and because of the increased difference in effective indices. This index difference goes slightly down for diameters below approximately 2.2 µm (see Fig. 1c), which explains the final drop in frequency. Another similar curve, although much fainter is visible on the spectrogram, and corresponds to interferences between the HE_{11} mode and another higher-order mode; a more quantitative approach could determine which mode exactly, through the numerical calculation of the accumulated optical path difference [4]. The lights of the lab also show up on the spectrogram in the form of a slight component at a constant 100 Hz frequency.

Using this setup, students can fabricate microfibres with a transmission greater than 90 % in a reproducible way, and are then ready to couple light into a WGM resonator.

Coupling to a microsphere

WGM resonators are manufactured using standard telecom equipment by fusing the extremity of a piece of single-mode fibre with a fiber splicer operating • • •

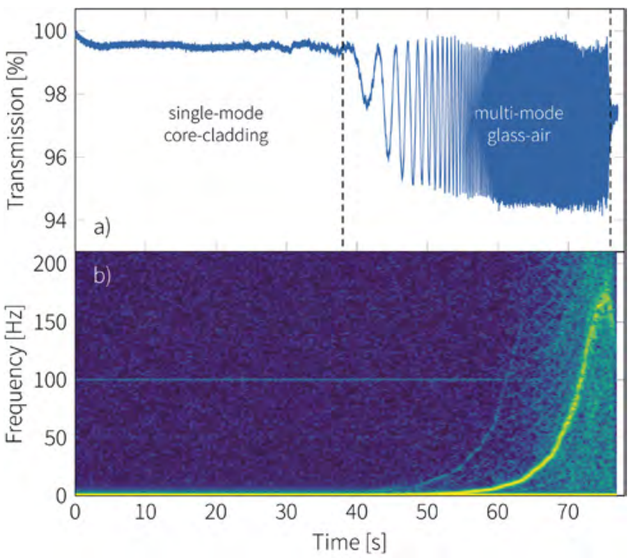


Figure 3. a) Normalized signal from the photodetector at the output of the fibre. Modal interferences appear after a few tens of seconds after the motors are started, their frequencies increase until they suddenly vanish. b) Spectrogram analysis of the previous signal revealing the presence of a strong component whose frequency increases before disappearing.

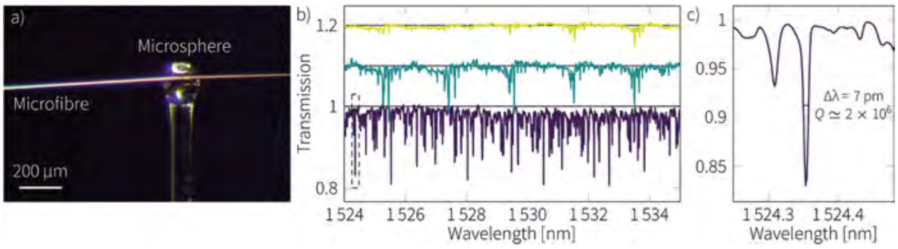


Figure 4. a) Microscope image of a microfibre coupled to a microsphere. b) Transmission spectrum of the sphere over a few free-spectral ranges, for different coupling positions. c) Enlarged section of the spectrum revealing a narrow resonance.

in manual mode. Due to surface tension of the melted glass, a sphere-like concave shape sustaining WGM is spontaneously obtained at the end of the fibre after fusing it and let it cool down to room temperature. As shown in Fig. 4 a), using manual translation stages under a binocular, students manipulate this micro-sphere in the vicinity of the previously fabricated microfibre to achieve an evanescent coupling between them.

To observe resonances, a tunable laser source with a narrow spectral linewidth is required. A research-grade external-cavity laser is the most convenient tool for this task, but a temperature-controlled distributed-feedback laser can be used instead. The injection and collection of light is performed through the microfibre, and the recorded signal as the laser wavelength is swept look like the ones presented in Fig. 4b). The different curves correspond to different contact positions on the microfibre: for the top one, the microsphere touches the microfibre where its diameter is still large, such that the evanescent field does not extend very far. Consequently, the resonances are not very pronounced, and only a few modes are coupled. In contrast, the bottom curve corresponds to a contact close to the waist of the microfibre. A larger number of resonances is visible, and the dips are more pronounced. A detail of the latter curve is shown in Fig. 4c) and reveals a sharp dip with a width of 7 pm only, corresponding to a quality factor of 2×10^6. While record quality factors in silica microspheres can reach 10^{10} [5], such a value remains remarkable in the context of labworks, and should be compared to other systems such as mechanical resonators, RLC circuits and quantum transitions.

The spectral distance between two consecutive resonances, the *free spectral range* of the resonator, can also be retrieved from the middle signal of Fig. 3b. An almost periodic structure is indeed visible, with a period of 1.98 nm, or 247 GHz if expressed in frequency terms. This frequency is the inverse of the time that light spends to make a full round-trip around the sphere: $\tau = \frac{n_m \pi D}{c}$ where n_m is the group index of the mode and D the diameter of the sphere. Assuming a value for n_m of 1.2 gives an estimated diameter of 300 µm for the microsphere, which is compatible with the microscope image of Fig. 4a. At this stage, these observations can be used as a basis for more in-depth discussions with interested students on the details of data analysis, how to extract modal dispersion, and how to sort mode families.

Conclusion

The experiment described in the present article is an attempt to illustrate various notions of wave optics that are taught at master's level: propagating modes, evanescent field and evanescent coupling, resonances. These concepts are necessary to explain the striking features of the experiment: appearance and disappearance of interferences, coupling of light from one object to another with a simple physical contact, extremely narrow resonances. This labwork is also an opportunity to familiarize students with the handling of standard equipment from fiber optics technologies, from splicer to translation stages, and from lasers to photodetectors. As part of the courses of the Master of Physics, Photonics and Nanotechnology from the EIPHI Graduate School in Bourgogne Franche-Comté, more than 100 Master students have been carrying out this experiment in a 4-hours labwork for the past 6 years. The experiment is also available as a pedagogical resource on the SMARTLIGHT platform at the Laboratoire Interdisciplinaire Carnot de Bourgogne (France)

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