Guiding light through an air hole: a new fascinating technology for metrology

A Hollow Core Photonic Crystal Fibre (HC-PCF) is something more similar to solid-state physics than classical optics. It propagates light in a central hollow core with a typical diameter of a few 10 µm. Once the technologies for the fabrication will become mature, these fibres could become the ultimate fibre for optical fibre telecommunications and a series of very promising application in metrology.

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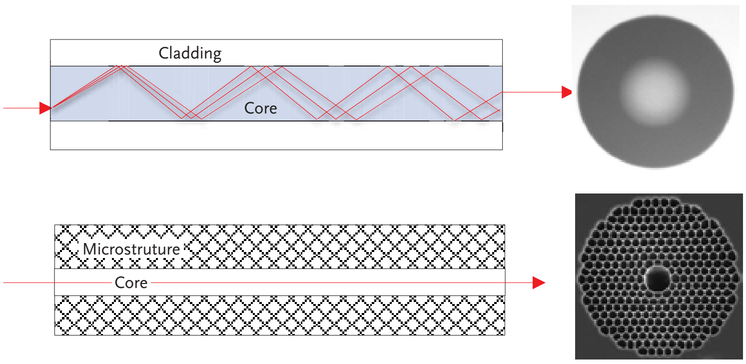
Standard optical fibres represent a powerful tool for transmitting light over long distances in a very easy way. These fibres are in general made of silica; the guiding mechanism is the total internal reflection of the light, thanks to the larger index of refraction of the silica core with respect to the surrounding medium (cladding), as shown in Figure 1 (top). The large majority of optical fibre transmission lines for telecommunication applications are based on this principle.

In the late 1980s, a new technique to guide the light was demonstrated, which is based on photonic bandgap structures, something more similar to solid-state physics than classical optics. This technique makes possible to confine light very efficiently without total internal reflection and to tailor the propagation characteristics with an unprecedented flexibility by adjusting the size and the geometry of tiny hollow microstructures all around the guiding region. This concept gave birth to the Photonics Crystal Fibres (PCF), which allows for example confining light in a tiny hollow core only filled with air. Figure 1 (bottom) shows the transverse cut of a Hollow Core Photonic Crystal Fiber (HC-PCF), in which light propagates in a central hollow core with a typical diameter of a few 10 µm. Due to the absence of material in the core, these fibres could potentially break the ultimate loss limits of standard silica based fibres and become the ultimate fibre for optical fibre telecommunications, once the technologies for the fabrication of these fibres will become mature.

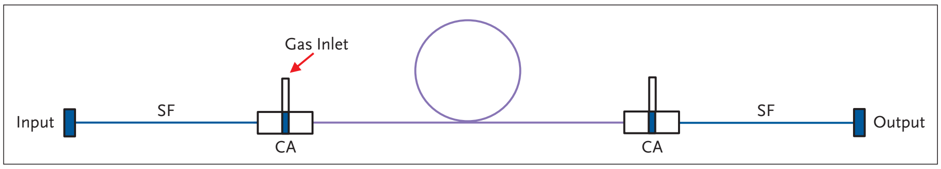


Applications

HC-PCF are not only promising for optical fibre telecommunications. They also pave the way to a series of very promising applications in metrology, especially when an efficient interaction between light and matter needs to be achieved. This can be done by filling the hollow core of the fibre with a specific gaseous or liquid substance and by simultaneously coupling light into the same region. The high confinement in the hollow core and the long interaction length allow achieving a very strong light-matter interaction, and thus efficiently measuring the spectral properties of the substance. This specificity is particularly interesting for the fabrication of improved and highly compact wavelength standards.

METAS developed, in the frame of the European Research Project EMRP IND14 Frequency, a fully all-fibre gas cell allowing to replace classical bulk gas cells with a very compact and versatile structure. This was achieved by developing a series of dedicated technologies and unique coupling devices for the gas filling of the PC-HCF and for the interfacing of the HC-PCF with standard telecommunication fibres. Figure (2) shows the structure of the all-fibre wavelength standard. The central part consists in a piece of PC-HCF, which is sandwiched between two connectorized standard optical fibres. A special connector adapter (CA) allows simultaneously performing an efficient coupling of the light between the fibres and also giving a vacuum tight access to the hollow core for the gas filling. Acetylene was considered, since this molecule shows a large number of absorption lines in the 1550 nm wavelength domain, which is the privileged region for the optical fibre telecommunications.

1: Two different guiding mechanisms: Total reflection in standard fibres (top), and photonic bandgaps (bottom).



2: Schematised all-fibre cell; HCF: hollow-core fibre; SF: standard silica fibre; CA: connector adapter.

This results in an all-fibre compact, robust and self-aligned system, which can be used for spectroscopy, laser stabilisation, or as wavelength standard for metrology. This technology allows fabricating gas filled structures (gas cells) with an interaction length of a few meters in a highly compact way, as shown in Figure (3).

Compactness and high end technologies are interrelated

Fabricating a compact all-fibre gas cell requires a careful control of many critical issues. Ideally, a low optical insertion loss and a minimum back-reflection are required, together with a very good control of the gas pressure and purity in the PC-HCF fibre. One of the key issues is the connection between the PC-HCF hollow core fibre and the input and output standard fibres. We developed for that purpose a unique device, in which the two fibres are self aligned and placed in close contact (butt coupling) for an optimum transmission of the light. This device also allows accessing the hollow core for the gas filling, and guarantees a long term stability of the gas pressure in the PC-HCF. Figure 4 shows the principle of the coupling device, together with its practical realisation.

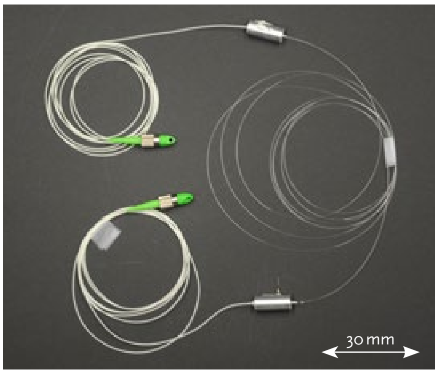
Fabricating a gas cell requires first evacuating the water vapour and other residuals deposited inside of the gas cell by connecting the capillary gas inlets to a dedicated vacuum pumping system and by sealing them with a plasma torch when the gas filling is finished.

High pressure acetylene wavelength standards

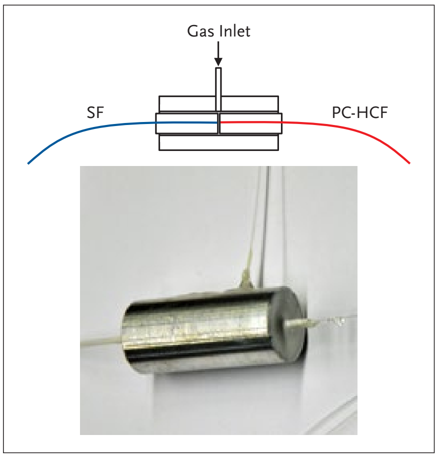
Many wavelength measuring instruments like the Optical Spectrum Analysers (OSA) require an internal wavelength standard for self calibration purposes. Our new technology proved to be very promising for this kind of application. Figure 6 shows the P17 absorption line of a $^{12}C_2H_2$ acetylene all-fibre gas cell filled at a pressure of 400 Pa and measured with a high resolution optical spectrum analyser. For that purpose the gas cell was illuminated using a broadband light source. Comparisons with classical wavelength standards and with reference spectral databases (HITRAN) allowed demonstrating a wavelength accuracy far below 1 pm.

Laser stabilisation

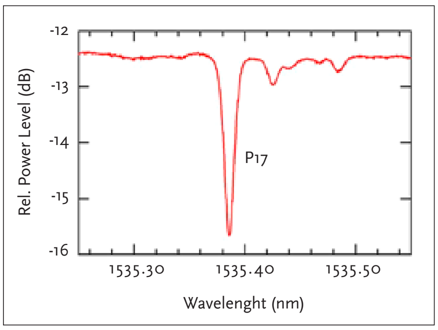
Compact PC-HCF gas cells are also promising for laser frequency stabilisation on a molecular line. This technology allows fabricating long gas cells with large absorption values at low gas pressure, which is particularly interesting for this kind of application. This was demonstrated by stabilising an all-fibre tuneable laser (AFTL) to the P16 line of a gas cell filled with the isotope $^{13}C_2H_2$ of acetylene at a pressure of 70 Pa. Figure 7 shows the absorption line on which the laser is stabilised. This isotope is one of the reference molecules commonly used in metrology.



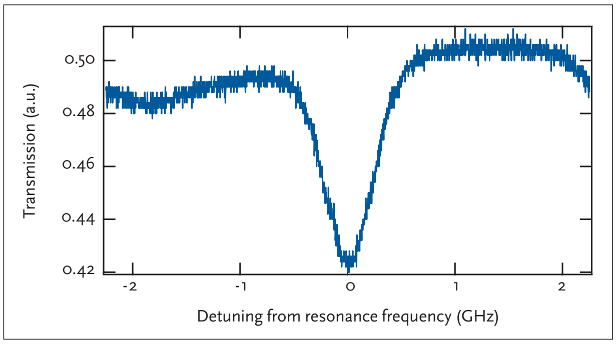
3: shows the practical realisation of an acetylene filled PC-HCF gas cell. The overall length of the fibre is a few meters. The very compact and flexible structure of the gas cell allows an easy implementation of such standards in measuring instruments.



4: Gas tight connector adapter, principle and practical realisation.

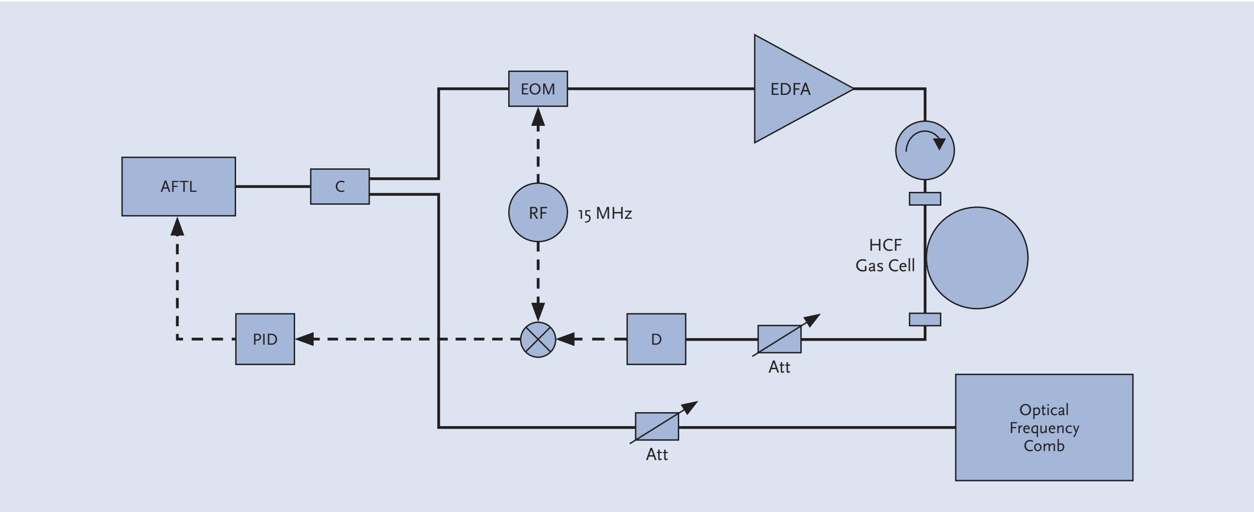


6: Doppler linear absorption of the P17 line of $^{12}C_2H_2$.

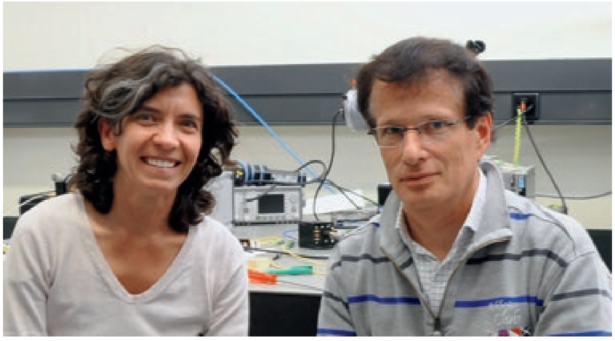


7: P16 line of $^{13}C_2H_2$ as seen by tuning an AFTL source around the resonance frequency.

The point of minimum transmission corresponds to the resonance frequency. With a clever electronics it is possible to force the laser to emit at this particular frequency. We obtain thus a frequency stabilised laser source, whose accuracy is orders of magnitude better than what an OSA can measure. In the case of a stabilised source, also the evolution of the frequency accuracy in time (frequency stability) is an important parameter. By direct comparison with the METAS self-referenced optical frequency comb we have measured both these parameters and obtained a relative frequency accuracy of a few 10^{-8} and a relative stability better than 10^{-9} when measured over 1s. Figure 9 shows the scheme of the setup used for frequency stabilising a laser source.



9: All-fibre optical setup for linear spectroscopy and laser stabilisation. AFTL: all-fiber tuneable laser; C: coupler; EOM: electro-optic modulator; EDFA: erbium-doped fiber amplifier; Att: attenuator; D: detector; PID: proportional-integral-derivative controller for laser lock. The Optical Frequency Comb allows to measure the frequency stability of the stabilised laser.



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Outlook

Wavelength standards are very important in many domains like optical fibre telecommunication, especially when considering the dense wavelength multiplexing techniques (DWDM) used to increase the transmission capacity of communication links, or for sensors, and of course in metrology. All-fibre wavelength standards have the potential to strongly contribute to further improvements in this field. The ultimate performance of such standards is still limited by the quality of the PC-HCF, which strongly depends on the maturity of the fabrication processes. The increasing demand for this kind of new components should contribute to a rapid development of improved PC-HCF, as it has been the case in the 1970's with the rapid development of improved silica based bulk fibres for optical telecommunication.