Waveguide and Gas: the Advent of a New Tool for Photonics

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Abstract *The realisation of hollow-core fibres and nano-waveguides offers a unique opportunity to optimise the interactions between light and a gaseous medium. Stimulated Brillouin scattering is exploited to achieve unprecedented levels of amplification and to realise efficient all-optical processing.*

Introduction

A significant progress in fibre optics has been the creation of hollow-core optical fibres, showing losses that will certainly reach lower values than those in all-silica fibres in a near future [1]. The lateral guidance of the light is achieved by means of ultrathin anti-resonant microstructures and the presence of the optical field in the silica is reduced to its tiniest fraction. As a result, losses are greatly reduced, as well as chromatic dispersion and the presence of limiting non-linear effects, such as modulation instability, 4-wave mixing and stimulated inelastic scatterings.

On the other hand, the absence of light-matter interactions drastically reduces the possibilities to amplify light in this type of waveguide and to perform sophisticated all-optical functions.

However, it has been recently demonstrated by our team that stimulated Brillouin scattering can be exploited in a particularly efficient way [2], not only to create unparalleled non-linear optical amplifications, unmatched even in dense optical materials, but also to realise complex optical functions and even more efficient sensors.

Principles

Stimulated Brillouin scattering in gases has so far been largely overlooked, at least in guided optics. At first glance, the gaseous medium should have been estimated too tenuous to give rise to significant effects. This view is fully correct under ambient conditions of temperature and pressure; however, the situation changes drastically when the gaseous medium is compressed, even without reaching extreme pressures.

The intensity of the optical interaction based on stimulated Brillouin scattering is directly related to the magnitude of the refractive index variation, normalised to the power of the optical waves causing this effect. This variation is induced by the acoustic wave created by electrostriction and is proportional to the polarizability of the molecules in the medium, the density of the medium and its compressibility. Notable differences are observed between solid and

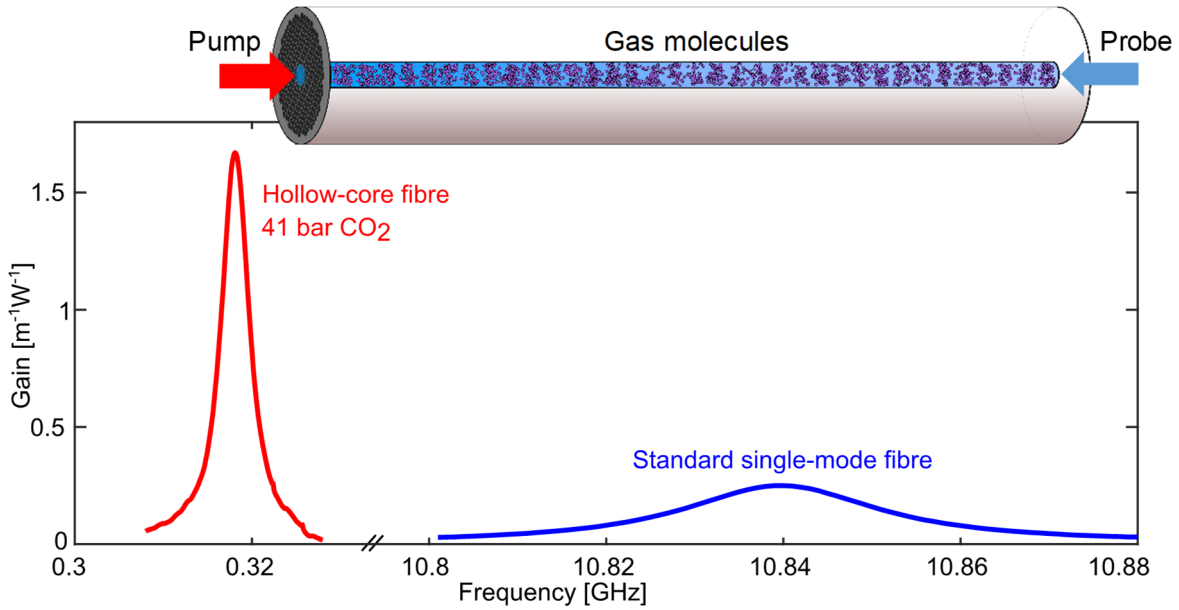

Fig. 1: Brillouin gain measured in a hollow-core optical fibre filled with high-pressure CO_2 (red) as a function of the optical frequency difference between pump and probe. As a comparison, the gain obtained in an all-silica fibre under the same measurement conditions is shown (blue). The horizontal scale is uniform, but broken due to the large gap in frequency differences. This shows that a significantly higher gain can be obtained in gas, at a much lower pump-probe frequency difference due to a slower acoustic velocity and with a narrower gain spectral width.

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gaseous media: in a solid, the density is high, but the compressibility is low, whereas in a gas the opposite situation prevails. Thus, in principle, there is no objective reason why the Brillouin gain in a gas should be low per se.

Actually, the higher compressibility of a gas does not compensate for the loss of efficiency due to its lower density under normal ambient conditions. Thus, the Brillouin interation turns out to be 2 orders of magnitude lower than that observed in a solid. However, by compressing the gas, its density will increase proportionally, while only marginally altering its compressibility, and the strength of the interaction should logically increase proportionally to the pressure.

In reality, the situation is even more favourable, since the acoustic losses in a gas decrease proportionally to its pressure. The pressure will therefore contribute another time to the efficiency of the interaction, which is expressed by a Brillouin gain that depends *quadratically* on the gas pressure. It is eventually sufficient to increase the gas pressure by a factor of ten to obtain gains comparable to those obtained in solids. And a pressure of a few tens of bars (i.e. a few MPa) can easily outperform the gains observed in ordinary solids, as shown in Fig. 1 in comparison with silica, and even surpass the best performing ones such as chalcogenides. Hollow-core fibres are proven to withstand pressures of several hundred bar, due to their miniature size.

The measured Brillouin gains for different gases (SF_6, N_2, CH_4 and CO_2) are shown in Fig. 2. Under identical pressure conditions, the gain of CO_2 is 3 times higher than that of CH_4, and 4 times higher than that of N_2. The Stokes shift (pump-probe frequency difference) is significantly different for these 4 gases, which means in practice that this shift can be customized to a large extent by changing gases or mixing them. These results lead to the following comments:

1. The Stokes frequency offset, or Brillouin shift, is directly proportional to the acoustic velocity. This velocity is high in a solid, giving a Brillouin shift of the order of 11 GHz in silica; however, sound propagates much more slowly in a gas, resulting in Brillouin shifts in the 0.1-1 GHz range. This lower frequency may be advantageous, as it enables the different interacting signals to be synthesised without using microwave modulation, but makes it more difficult to separate them through spectral filtering in the optical domain.
2. The Brillouin shift is specific to a given gas and can be finely tuned to a large extent by properly mixing distinct gases. The density also depends on the type of gas, which changes the Brillouin response accordingly. For a perfect gas, the density is proportional to the molecular weight *M*, so higher gains can potentially be achieved using more massive molecules, again with a quadratic dependence on *M*. However, it should be mentioned that gases containing large

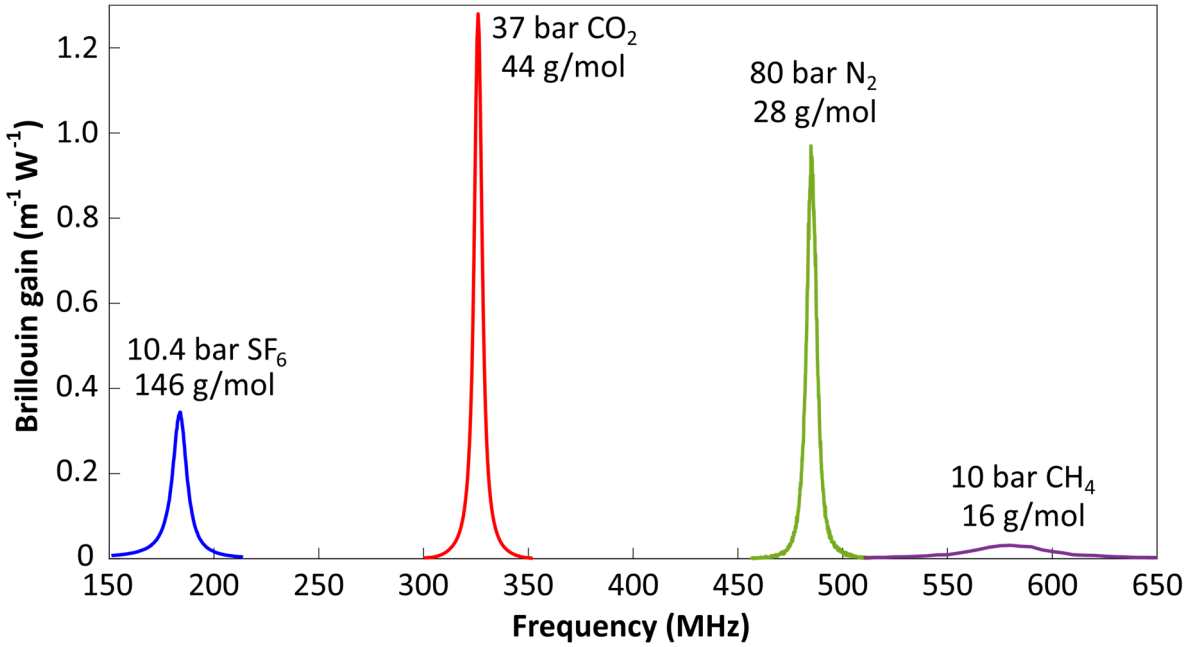

Fig. 2: Brillouin gain measured in a hollow-core optical fibre filled with various gases. Except nitrogen N_2, the pressures of the other gases are close to their liquefaction pressure and cannot be significantly increased. The difference in frequency between pump and probe reflects the difference in acoustic velocities for the various gases. At equivalent pressures, gases with a large molecular weight (shown in the figure) offer a higher gain [2].

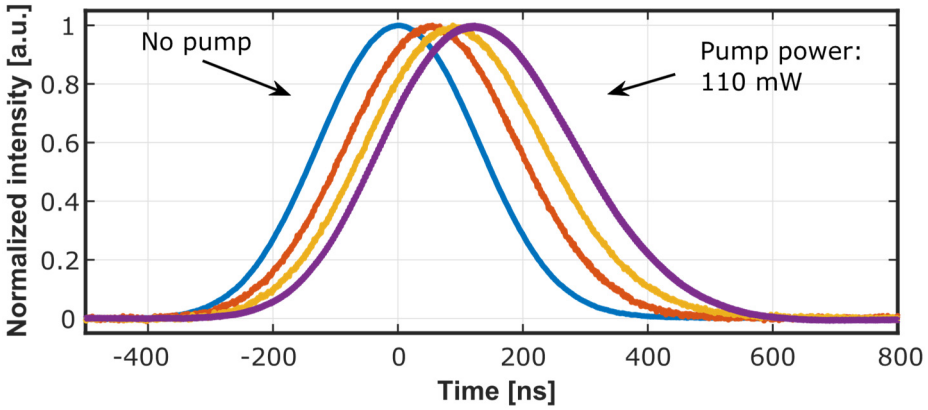

Fig. 3: Pulse propagation under slow light regime induced by stimulated Brillouin scattering in a 50 m hollow-core optical fibre filled with CO_2 at a pressure of 41 bar, showing increasing group delay when the pump power is raised.

molecules normally have a relatively low liquefaction pressure, negating most of the advantages of the higher molecular weight by setting a maximum value on the gain due to this pressure ceiling. In the case of a lighter molecule with no liquid phase at room temperature, higher gains can be practically achieved by simply increasing the pressure with no real limit. More complex molecules are also more likely to have spectral absorption lines close to the wavelength of interest, which can induce highly undesirable broad-spectrum attenuation due to the significant line broadening by molecular collision at high pressure.

3. The gas is inherently insensitive to strain applied to the fibre, which is an elegant way to solve the recurring problem of cross-sensitivity to temperature and strain in most all-silica fibre sensors, including Brillouin sensors. In hollow-core fibres, these sensors will be inherently insensitive to strain, so will give a response only to temperature.

Results and discussion

The Brillouin gains already demonstrated in gas-filled fibres exceed anything achieved in the best solid materials. For example, an amplification of 50 dB could be demonstrated over 50 m of hollow-core fibre filled with CO_2 at 41 bar using a pump power of 200 mW. This clearly opens up new perspectives, offering an elegant solution for amplification in these new fibres, moreover operating at any wavelength and with very high efficiency.

Virtually any sophisticated application based on stimulated Brillouin scattering demonstrated in all-silica fibres could be proven and realised equally well in hollow-core fibres [2]: fibre Brillouin lasers, slow light as illustrated in Fig. 3, and above all, even more efficient distributed sensors. For the latter, complete immunity to the effect of stresses has been demonstrated and the high gains allow for unparalleled performance in terms of accuracy and spatial resolution.

It should be mentioned that, while a straightforward implementation can be made in hollow-core fibres, other types of waveguide can exploit this type of amplification, using the evanescent part of their guided field. This way, significant gains can certainly be obtained with planar waveguides. The principle of exploiting the evanescent field has just been demonstrated with tapered nanofibers [3], for which a linear gain 79 times higher than in ordinary all-silica fibres has been realised, paving the way to a field of applications still largely unexplored, for on-chip amplification, sensors and for optical information processing.

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