Large Brillouin interaction in hollow core fibers

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Abstract: Brillouin gain is observed in hollow core fibers filled by standard gases at high pressure. This enables all interactions based on stimulated Brillouin scattering to be realized in hollow core fibers, such as amplification, optical signal processing and distributed sensing.
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1. Contextual introduction

A novel approach for light amplification in waveguides is introduced, based on the power transfer between an intense pump beam and a distinct signal wave to be amplified, using a nonlinear coupling. The linear gains achieved using this approach outperform the best achievements using any other nonlinear interactions in the best materials for optical waveguides. This approach exploits backward stimulated Brillouin scattering (SBS) in gases, which show very high interaction strengths under high gas pressure conditions, as shown in Fig. 1. Linear gains up to 1000X larger than in silica can be realistically achieved. This value is still 10 times larger than in chalcogenide glasses, considered like the most efficient waveguide materials for SBS interactions [1].

The advantages of coherent nonlinear amplification are numerous: gain can be induced in the medium at virtually any wavelength, amplification is distributed, spectrally-selective and directional and, in the case of SBS, the gain spectral profile can be precisely customised by a proper pump modulation.

For many aspects, realising functions directly in silica optical fibres is a very attractive approach: long lengths of optical fibres can be economically produced and the power loss inherent to a connection between heterogeneous waveguides is virtually inexistent. A preferred implementation is therefore in gas-filled silica hollow-core photonic crystal fibre (HC-PCF) to achieve unprecedented nonlinear optical amplification from near-ultraviolet to mid-infrared.

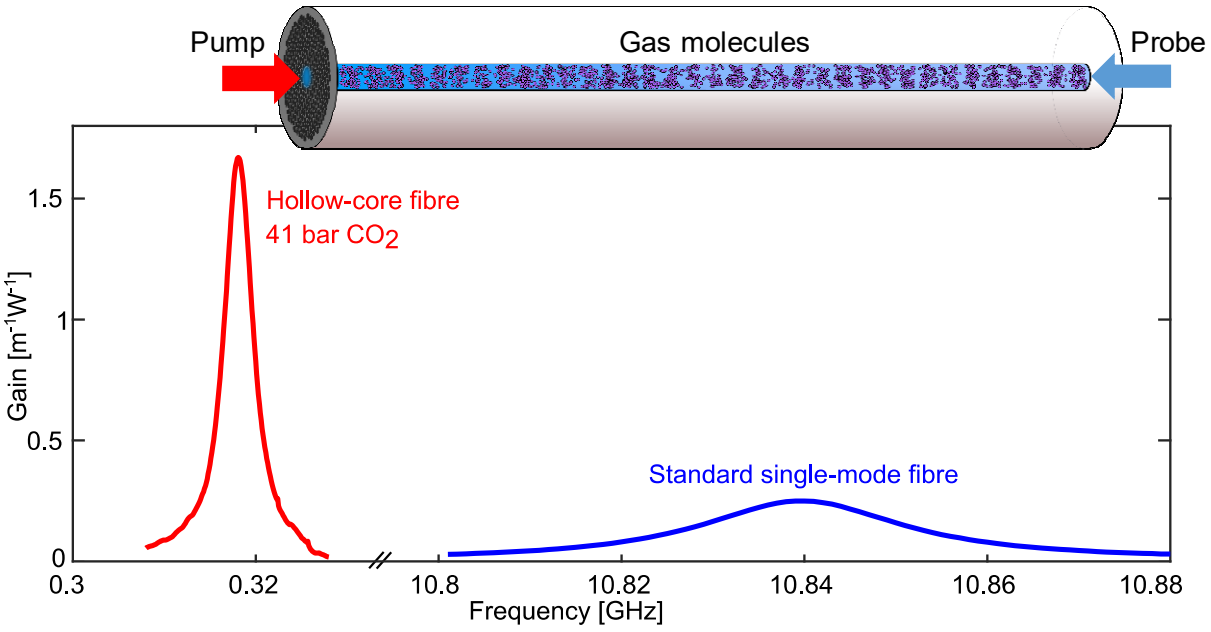

Fig. 1. Gain measured in a hollow-core photonic bandgap fiber (red) filled with CO2 gas at high pressure, as function of the optical frequency detuning between the pump and the counterpropaging amplified probe signal. For comparison the gain measured in a solid core silica fiber is also represented (blue). It demonstrates that a substantially higher gain is achieved in the gas, showing a narrower gain linewidth obtained at a smaller frequency detuning. The horizontal scale is broken for a better visualization, but kept unmodified.

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Stimulated Brillouin scattering cannot be reduced to a mere amplification process, since it has demonstrated its potentialities to realise advanced functions [2]. This novel gas-based Brillouin platform can be the foundation of many potential applications: amplifiers, highly coherent Brillouin gas lasers, slow & fast light, microwave filters, tuneable delay lines, light storage, all-optical calculus and of course sensing [3]. The same functions can therefore be implemented in hollow-core fibres, offering all the inherent assets of fibre-based optics, with the key advantage to realise the same response with a product *pump power* x *fibre length* 1000X smaller.

2. Principle & Realisation

The issue of optical amplification in hollow-core fibres has already given rise to sustained efforts and interesting results have been reported, mostly using atomic transitions in a low pressure gas (like in classical gas lasers) [4] or Raman gain in hydrogen [5, 6]. The obtained gains remain modest in both cases when compared to solid-core solutions, with the specific penalties of amplification at fixed wavelengths for atomic transitions and the issue of fast hydrogen permeation through the glass walls for Raman amplification.

Exploiting guided-wave stimulated Brillouin scattering in gases has been so far widely overlooked by the community, with the notable exception of the observation of resonant transverse acoustic waves through the distinct process of forward Brillouin scattering [7]. Possibly, the common opinion has considered the Brillouin gain as much too small in such a tenuous medium to be practicable for useful amplification. This picture turns out to be fully correct in ambient conditions, but the situation is radically changing when the gas medium is densified, even without reaching extreme conditions.

The strength of the Stimulated Brillouin interaction is directly related to the absolute change of refractive index per unit power of the interacting waves. It is essentially proportional to the molecules polarizability, the nominal density of the medium and its compressibility [8]. There are specific differences between solid and gaseous: in a solid material, the density is high, but the compressibility is low. The reverse situation is observed in gases. So nominally, there is no fundamental reason to make the Brillouin gain vanishingly small in gases.

Actually, at ambient conditions, the gain in compressibility does not compensate the loss in density and the Brillouin interaction strength is effectively some 2 orders of magnitude smaller than in a solid. However, rising the pressure increases the density proportionally, but affects marginally the compressibility, so the interaction strength is expected to grow proportionally to pressure.

The situation is in reality even more favourable, since the acoustic loss decreases proportionally to the pressure. The pressure thus contributes a second time to increase the acoustic amplitude and the strength of the interaction eventually depends on the *squared* pressure. Concretely, by rising the pressure to a few tens of bars, Brillouin gains comparable to solid materials can be obtained. They may even be largely overcome by further rising the pressure to hundreds of bars, which is proved perfectly sustainable in hollow-core fibres [9].

Preliminary experiments fully confirmed these intuitive predictions, as shown in Fig. 2. The gain resonance obtained in nitrogen is clearly visible and its peak value grows with a squared dependence on pressure. Based on the same progression, amplification comparable to silica – which is still 10 times larger than the peak value at 6 bars of N_2 – are predicted to be reached with ~20 bars of nitrogen.

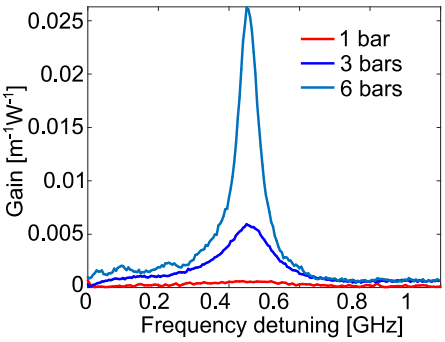

Fig. 2 SBS gain in nitrogen at different pressure (normalised to the fibre length and the pump power) experienced by the probe light as a function of the frequency detuning between the interacting waves.

Table 1. SBS gain in gas-filled HC-PCF at a pressure of 10 bar of N_2, CH_4 and CO_2 at 24 °C.

Gas	**Name**	ν_B [MHz]	$\Gamma_B/2\pi$ [MHz]	g_0 [$m^{-1}W^{-1}$]
N_2	Nitrogen	451	41	0.025
CH_4	Methane	580	40	0.034
CO_2	Carbon dioxide	351	21	0.105

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The measured backward SBS gain for different gases such as N_2, CH_4, and CO_2 under the same condition (at 10 bar pressure and 24 °C) are shown in Table 1. The gain of CO_2 is 3 times larger than CH_4 and 4 times larger than N_2. The Brillouin frequency shift is different for these three types of gases, which means we can tune the Brillouin frequency shift by using different type of gases. These results lead to formulate the following comments:

1. The frequency difference between the 2 interfering lightwaves, corresponding to the frequency of the acoustic wave and called *Brillouin shift*, is tightly related to the acoustic velocity, in direct proportion. It is high in a solid material, giving a Brillouin shift of some 10 GHz in silica, but the sounds propagates much more slowly in a gas, with corresponding Brillouin shifts in the range 0.1-1 GHz. This lower frequency may facilitate the synthesis of the different optical signals without using microwave modulation, but makes the spectral separation of these signals in the optical domain much more challenging.
2. The Brillouin shift is specific to a given gas and can be finely customized over a broad spectral range by a proper gas mixture. The density also depends on the gas species and this will modify the SBS response, accordingly. For an ideal gas, the density is proportional to the molecular mass *M*, so larger gains can potentially be obtained by using heavy molecules, with again a squared dependence on *M*. It must be noted that gases with large molecules normally show a liquefaction pressure that is relatively low, cancelling most benefits from the higher molecular mass by setting a maximum value for the gain. A lighter molecule showing no liquid phase at ambient temperature may eventually deliver higher gains by simply rising the pressure. More complex molecules are also more likely to present spectral absorption lines near the wavelength of interest, which may induce a spurious attenuation over a wide spectrum as a result of the large pressure line broadening. Gain can also be scaled by varying pressure and mixture.
3. The gas is by essence insensitive to deformation applied to the fibre, so it is an elegant way to solve the constant issue of the temperature-strain cross-sensitivity in most fibre sensors, including Brillouin sensors in silica. In hollow-core fibres such sensors will be by essence sensitive to temperature only.

A synoptic comparison of the material linear Brillouin gain (in m/W) using different interactions and materials is shown in Table 2, including predictions for backward SBS in nitrogen at 1000 bars, based on a physical model. It can be noticed that backward SBS in gas provides the weakest gain under ambient conditions, but eventually outperforms all other configurations under high pressure.

Table 2. Comparison of linear gains in different materials and for different nonlinear interactions

	SBS in silica	SBS in chalcogenide [1]	Raman gain in H_2 at 10 bar [5]	Forward Brillouin gain in air [7]	SBS in N_2 at 1 bar	SBS in N_2 at 1000 bars
Linear gain (m/W)	3×10^{-11}	6×10^{-9}	4.2×10^{-12}	4×10^{-14}	3×10^{-14}	3×10^{-8}

The envisioned potentialities are very large and the implementations practically realistic, with huge amplification in the range of 50 dB over less than 100 m of fibre and sub-watt pumping powers.

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3. References

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