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# EFFICIENT GENERATION OF COHERENT STOKES FIELD IN HYDROGEN GAS-FILLED HOLLOW CORE PHOTONIC CRYSTAL FIBRES

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**Abstract.** *We study the coherent Stokes generation in a transient stimulated Raman scattering regime by Hydrogen gas-filled hollow-core photonic crystal fibres configuration. The temporal and spatial evolution of the pump and Stokes field envelopes as well as the coherence and population inversion are numerically calculated. The Stokes generation efficiency and the influence of pump pulse width and gas pressure on the energy exchange along fibre are investigated.*

Keywords: coherent Stokes generation; stimulated Raman scattering (SRS); gas filled HC-PCFs (hollow-core photonic crystal fibres) .

Classification numbers: 42.65.Dr.

## I. INTRODUCTION

The ability of remaining the high molecular coherence degree with the initial pump field in the transient stimulated Raman scattering (SRS) regime [1] makes it become a promise candidate for generating the ultrashort pulse compressed by coherent Raman frequency comb [2, 3]. However, the achievement of that regime in gas is difficult, it requires the applied pump pulse must be intense, ultrashort [2, 4]. Gas filled HC-PCFs (hollow-core photonic crystal fibres) with the excellent properties opens the opportunity to study the transient SRS regime in gas by very long pump pulse duration [5, 6], and discover a lot of interesting processes in SRS [6–11]. In SRS, the pump pulse width and the gas pressure filled inside HC-PCFs play an important role to optimize of interaction Raman efficiency and to generate Stokes frequency, especially to choose input parameters for desired Stokes field. In this work, we study with numerical calculation the temporal and spatial evolution of the pump and Stokes field envelopes along Hydrogen gas-filled HC-PCFs. The effects of active gas pressure and pump pulse width on the coherent Stokes generation efficiency are also discussed.

## II. COHERENT STOKES GENERATIONS IN $H_2$ GAS-FILLED HC-PCFs

The scheme of coherent Stokes generation is described in Fig. 1, the coherent Raman interaction equations and its solution were presented in Ref. [12] where the pump, $E_P$ and Stokes, $E_S$ Gaussian fields are in co-propagation in HC-PCFs filled with $H_2$ gas. The pump pulse width is in the range for transient SRS regime [5].

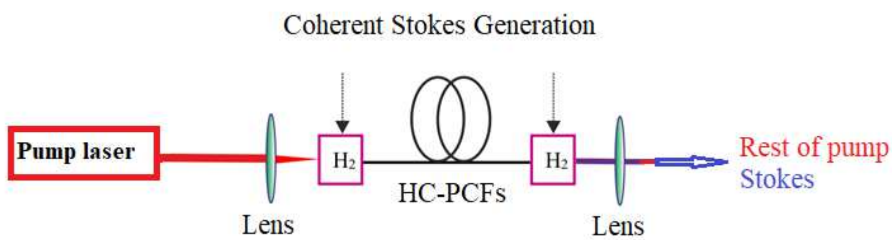



**Fig. 1.** The illustrated scheme of coherent Raman generation in $H_2$ gas filled HC-PCFs.

In this model, gas pressure and pump pulse width are controllable. Because HC-PCFs allows gas-laser intensity tight confinement in a small effective cross-section at relatively low input pump powers, it could potentially increase the Raman linewidth, the dephasing times $T_2$ (the inverse value of Raman linewidth) on $H_2$ gas pressure in HC-PCFs was shown in Fig. 2.

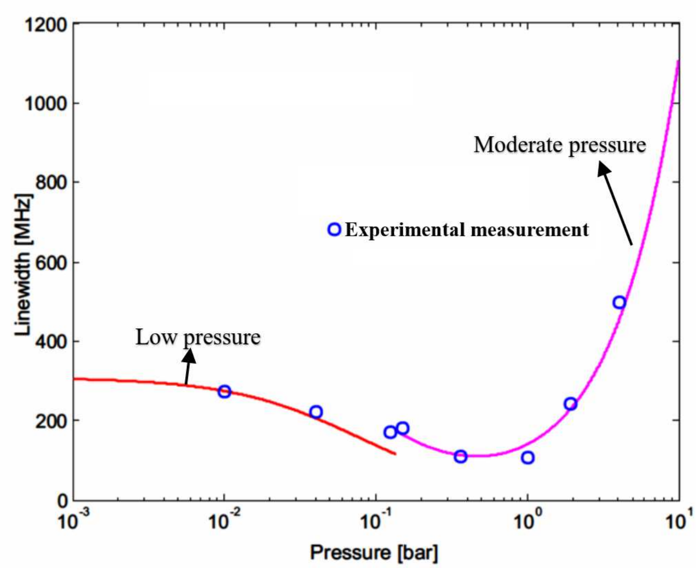



**Fig. 2.** The total Raman linewidth vs. $H_2$ gas pressure filled into HC-PCFs [13].

In the low gas pressure region (below 20 mbar), the linewidth for forward scattering is dominant by Doppler broadening effect. When the gas density increases, molecular collision begins to contribute to the spectral lineshape. If this collision is an elastic velocity-change process, meaning that do not affect the internal state of molecules, the line shape will reduce when the mean-free path of collisions is about the scattering wavelength (solid-curve in range gas pressure $< 0.1$ bar). When the gas density increases significantly (above 500 mbar), the line shape is broadened by the internal state-changing collisions of the gas molecules (solid-curve in the range 0.1 bar $<$ gas pressure $<$ 10 bar). Experimental measurements were shown by circles in Fig. 2 [13].

## III. RESULTS AND DISCUSSIONS

### III.1. Coherent wave propagation along fibre

Figure 3 shows the temporal and spatial evolution of the pump and Stokes field envelopes along the HC-PCFs with length $z = 4$ m, filled $H_2$ gas at pressure of 1 bar. The Stokes field envelope's growth (Fig. 3b) is caused by the decrease of pump envelope (Fig. 3a) along the fibre. It is clear that the most of initial pump energy is transferred into the Stokes energy. The energy transfer mechanism between pump - Stokes - coherence fields were explained in Ref. [11].

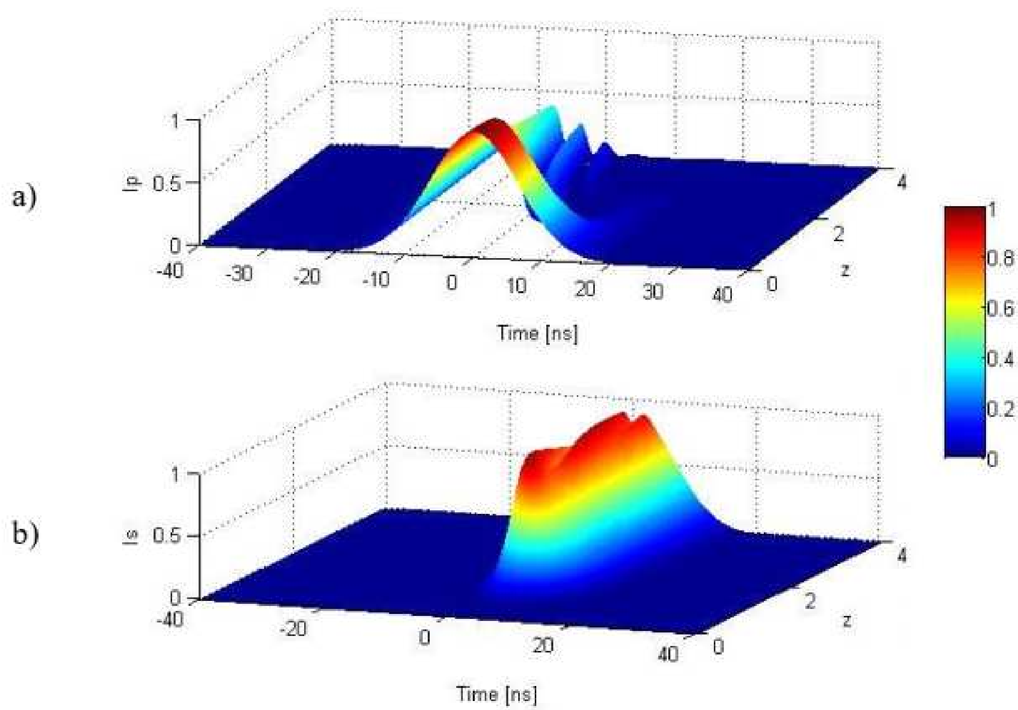



**Fig. 3.** Temporal and spatial evolution of pump (a) and Stokes (b) field envelopes along the HC-PCFs at gas pressure of 1 bar and pump pulse width of 15 ns.

The formation and evolution, in the time-space phase plane (t, z), of the coherence and population inversion are presented in Fig. 4. It shows that coherence and population inversion slowly increase and achieve their maximum values when the Stokes is well generated at z ∼1.2 m, at which population inversion get a maximum value and saturates in time.

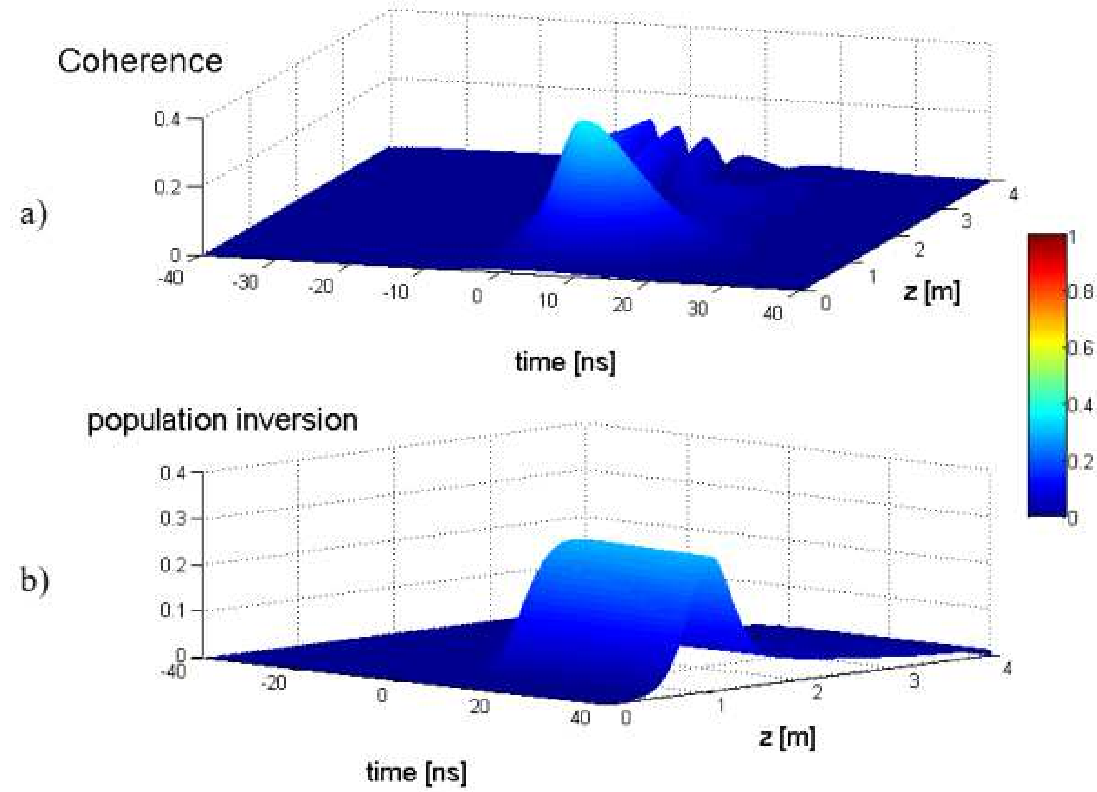



**Fig. 4.** Temporal and spatial evolution of absolute value of coherence (a) and population inversion (b) at gas pressure of 1 bar and pump pulse width of 15 ns.

### III.2. Efficiency of Stokes generation

Energy exchange between the pump and Stokes fields along a fibre length of 20 m filled of 1 bar $H_2$ gas pressure, pump pulse width of 15 ns is calculated and presented in Fig. 5. At the input position of fibre, z =0, the Stokes energy is quite small and the system energy is normalized to coupled pump energy. The Stokes field is uniformly amplified or the spontaneous process appears along fibre shorter 0.5 m, and then the energy exchanging process is strongly happened for longer fibre and get 50% when fibre is 0.76 m length (at $z = 0.76$ m). More interestingly, Fig. 5 also shows that optimal fibre length of about 3.5 m for the highest Stokes generation efficiency of 80% exclusively exists. The optimization of fibre length is seem to be an important choice for Raman generation experiments if gas pressure and pump pulse width are suitably given.

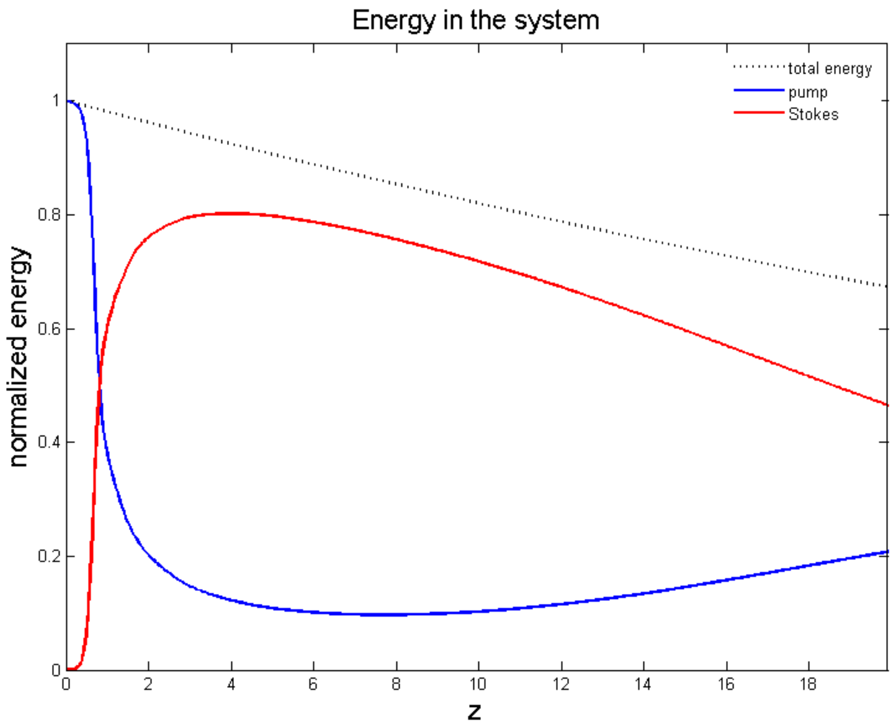
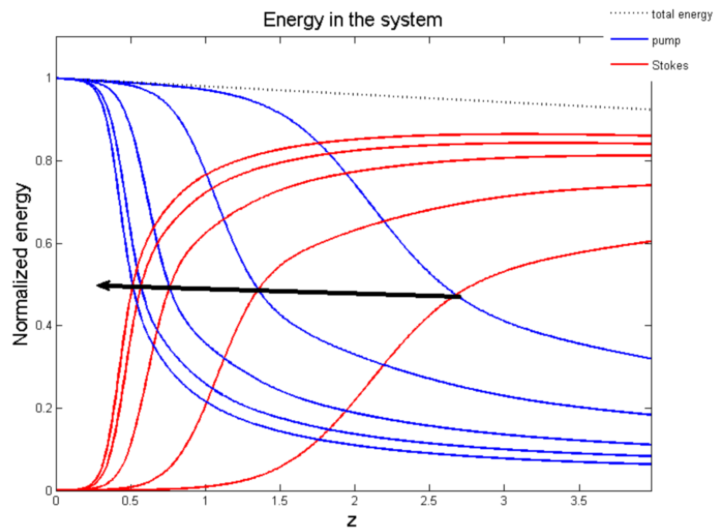



**Fig. 5.** Energy exchange between pump and Stokes along 20 m of HC-PCFs at gas pressure of 2 bar and pump pulse width of 15 ns.

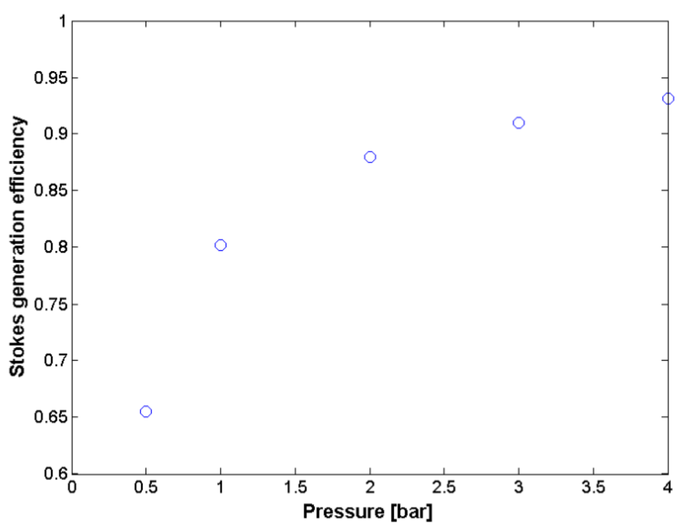
***Effect of gas pressure***

Now, we adjust the pressure of $H_2$ active gas from 0.5 bar to 4 bar ($T_2$ is calculated in Fig. 2) at pump pulse width of 15 ns, the curves of pump - Stokes energy exchange are plotted in the direction of black arrow in Fig. 6a. The output Stokes efficiency depends on the gas pressure filled in 4 m of HC-PCFs is shown in Fig. 6b, in which output Stokes efficiency is presented by the circles for the gas pressure 0.5 bar, 1 bar, 2 bar, 3 bar and 4 bar.

It also shows that coherent Stokes generation efficiency increases with gas pressure's growth, however, at the given pump pulse width and fibre length, it is not proportional to the gas pressure that slowly increases to the limit energy line (dash line). The Stokes generation efficiency at output surface of fibre archives approximately 93% at gas pressure of 4 bar and 65% at that of 0.5 bar. This causes by the robust increment of Raman linewidth resulting from the destroy of molecule system's coherence (see Fig. 4a). Therefore, it requires longer fibre for lower gas pressure to archive higher Stokes efficiency. Consequently, we can control the Stokes generation efficiency in the range of certain gas pressure at a given fibre length. Interestingly, the intersection point between the Stokes efficiency curve and pump one seems to be on the Stokes efficiency straight line of 50%.



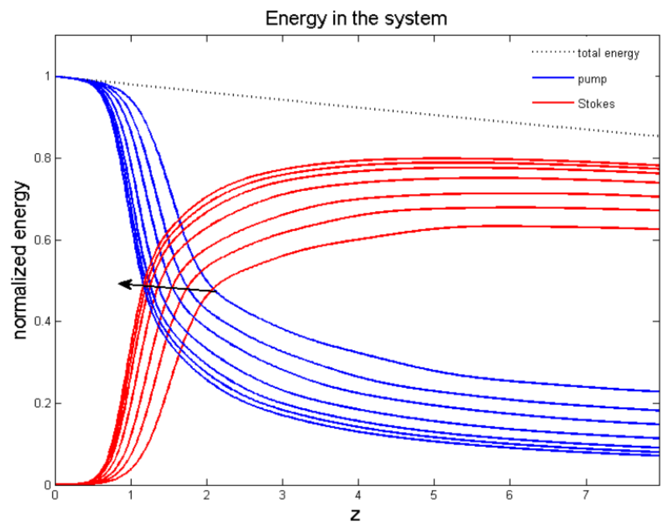

a)



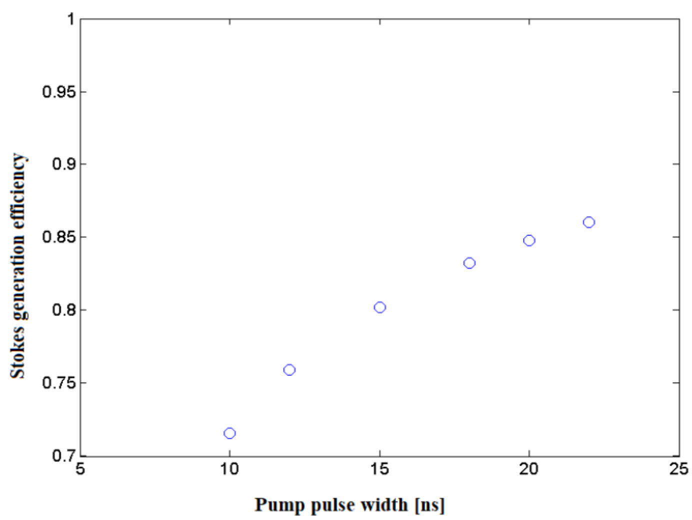

b)

**Fig. 6.** Dependence of coherent Stokes generation on $H_2$ gas pressure filled into HC-PCFs at pump pulse width of 15 ns, fibre length of 4 m: a) Energy exchange between pump and Stokes with gas pressure variation (0.5 bar, 1 bar, 2 bar, 3 bar and 4 bar) , b) Output Stokes generation efficiency vs. gas pressure.

### *Effect of pump pulse width*




a)




b)

**Fig. 7.** Dependence of coherent Stokes generation on the pump pulse width at gas pressure of 1 bar, fibre legth of 8 m: a) Energy exchange between pump and Stokes change with the change of pump pulse width, b) Output Stokes geration efficiency vs. pump pulse width (10 ns, 12 ns, 15 ns, 18 ns, 20 ns, 22 ns).

When the pump pulse width is changed in the range of 10 ns -22 ns, at 1 bar gas pressure and constant peak power, the energy exchange curves are calculated and shown in Fig. 7a, the direction of arrow shows the pump pulse width's growing direction. Fig. 7b shows the dependence of the

Stokes generation efficiency on pump pulse width in the range of 10 ns -22 ns. Larger pump pulse width gives higher Stokes generation efficiency at the given length of fibre and gas pressure. This efficiency increment is gradually slower when the pump pulse width becomes larger, this could be caused by the increase of collisional dephasing rate for larger pump pulse widths and reach a steady state (saturation). Of course, it is not linearly proportional to the pump pulse width that slowly increases to the limit energy line. Stokes generation efficiency gets approximately 86% at pump pulse width of 22 ns and 65% at that of 10 ns. Hence, in order to archive the highest efficiency, it is necessary to choose a suitable length of fibre for a given pump pulse width.

Consequently, we also control the Stokes generation efficiency in the range of certain pump pulse width at the given gas pressure and fibre length. The intersection point between the Stokes efficiency curve and pump one also seem to be on the Stokes efficiency straight line of 50%, like the case of gas pressure change. These give us another simple way to enhance the Raman generation efficiency instead of using other complex Raman generation system with special hollow fibre structure [14, 15] or tailor polarization [16].

## IV. CONCLUSIONS

We study with numerical calculation the coherent Stokes generation in a transient SRS regime by Hydrogen gas-filled HC-PCFs configuration. The temporal and spatial evolution of the pump and Stokes fields along Hydrogen gas-filled HC-PCFs, as well as the effects of gas pressure and pump pulse width on the coherent Stokes generation efficiency have been investigated and discussed. Interestingly, we prove that coherent Stokes generation efficiency can be controlled and, therefore, optimized by changing of gas pressure and pump pulse width at a given length of HC-PCFs. In this process, the intersection point between the Stokes efficiency curve and pump one seems to be on the Stokes efficiency straight line of 50%. These obtained results are useful for predicting the processes of coherent Raman generation and reducing experimental works.

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