Ultra wide band supercontinuum generation in air-silica holey fibers by SHG-induced modulation instabilities

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Abstract: Second harmonic generation in an air-silica microstructured optical fiber pumped by subnanosecond pulses is used in order to initiate modulation instability processes in normal and anomalous dispersion regimes. This allows us to generate an ultra wide and flat supercontinuum (350-1750 nm), covering the entire transparency window of silica and exhibiting a singlemode transverse profile in visible range.

OCIS codes: (190.4370) Nonlinear optics, fibers; (190.5530) Pulse propagation and solitons

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1. Introduction

The combination of microstructured optical fibers and subnanosecond microchip lasers allows to realize very compact and efficient systems leading to wide band supercontinuum generation [1-4]. In particular, homogeneous spectral broadening can be achieved in large normal dispersion regime by means of modulation instabilities (MI) induced by a double pumping system [5-6]. We show here that the same type of phenomenon can be observed by using a single pump laser and generating its second harmonic frequency directly in the fiber. We demonstrate that second harmonic generation occurring in the holey fiber is sufficiently efficient to initiate spectacular MI processes in large normal dispersion regime and to obtain a white light source with a single pump laser at 1064 nm.

The generated supercontinuum surprisingly extends from almost 350 to 1750 nm (limited by measurement), covering the entire transparency window of silica optical fibers. The spectrum is divided into two parts, on both sides of the pump wavelength, with a flatness of around 5 dB for each part. The transverse spatial profile of the output beam is singlemode and is built on the second order mode (LP_{11}) of the fiber in the visible range. No supercontinuum exhibiting such kind of performances and bringing such nonlinear processes into play was, to our knowledge, already published.

This white light source is suitable for many applications requiring low cost and compactness, such as Optical Coherence Tomography (OCT), confocal microscopy, hematological diagnosis or also spectroscopy. Some first measurements demonstrate the presence of energy in the UV range, opening a new field of possible applications of this technology.

2. Experimental set-up and characteristics of the microstructured fiber

The set-up is shown on Fig. 1. The pump source consists of a Q-switched Nd:YAG laser delivering 600 ps pulses at $\lambda = 1064$ nm. It is coupled into a 2-m long air-silica microstructured optical fiber by means of a focusing lens. A half wave plate is used to make the polarization rotate on the input end of the fiber.

The microstructured fiber, fabricated in our laboratory, has a hole-to-hole spacing Λ of around 2.2 µm and an average hole diameter of 1.5 µm, resulting in a ratio d/Λ equal to 0.68 and indicating that the fiber is highly nonlinear and slightly multimode [7]. This fiber exhibits two propagation modes (fundamental mode, LP_{01} and second order mode, LP_{11}) for wavelengths in the visible range and is strictly singlemode beyond 1200 nm. The transition between these two behaviors, around 1 µm, is gradual and permits to transfer more or less energy to the two transverse modes. The chromatic dispersion curves of these two modes have been calculated with a finite element method and are plotted on Fig. 2. For LP_{01} mode, the zero dispersion wavelength (ZDW) is located at 870 nm. For LP_{11} mode, it is shifted down to 710 nm and a second ZDW appears at 1100 nm.

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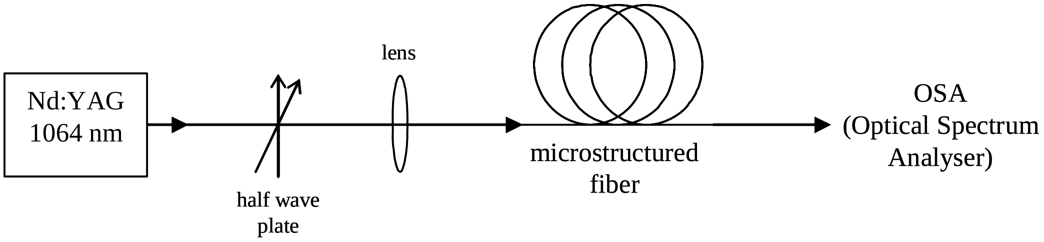

Fig. 1. Experimental set-up.

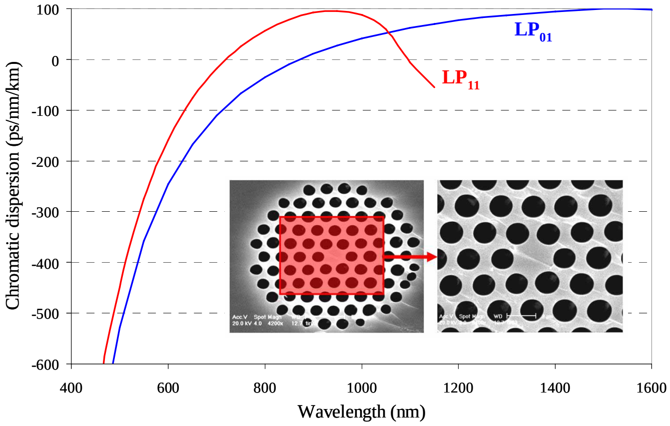

Fig. 2. Calculated chromatic dispersion curves of fundamental and second order modes of the microstructured fiber. Inset: cross sectional scanning electron microscope image of the fiber.

3. Second harmonic generation (SHG) in the microstructured fiber

When we launched the fundamental radiation (1064 nm) into the microstructured fiber, we clearly observed the generation of energy at 532 nm inside the fiber, corresponding to the doubling of the fundamental frequency [8-11]. This SHG is due to local inhomogeneities located in silica glass and also to the core-cladding interface, corresponding to the air-silica interfaces, encountered by the pump wave propagating in the core. The SHG efficiency remains weak (few %) but is sufficient to initiate MI processes and to generate a wide band supercontinuum, as shown underneath. Figure 3 shows an example of spectrum measured for a low pump power launched into the fiber: the pump line at 1064 nm is slightly broadened and the SHG line is visible at 532 nm.

4. Visible and infrared spectral broadening

It has been previously demonstrated [5-6] that a double pumping system (both 532 and 1064 nm pump wavelengths) could induce MI process leading to supercontinuum generation in large normal dispersion regime, over the whole visible range and without any presence of noticeable peaks due to stimulated Raman scattering (SRS). The phase matching condition was then achieved thanks to a strong nonlinear phase shift combined with the particular dispersion characteristics of the fiber, depending on the considered propagation mode (LP_{01}).

Identical MI process can be obtained by pumping the fiber at a single wavelength (1064 nm), the second wave (532 nm) being created directly inside the fiber by means of SHG. Indeed we obtained by this way the supercontinuum plotted on Fig. 4, which exhibits a wide and flat spectral broadening in the visible domain. A continuum was also observed in the infrared range, i.e. in anomalous dispersion regime, resulting from the combination of self and cross phase modulation, SRS and four-wave mixing. The whole broadening finally extends from 350 to 1750 nm (lowest and highest limits of the OSA used), covering the entire transparency window of silica. For each part of the spectrum, the flatness is around 5 dB. The visible part is 10 dB lower than the infrared one.

Finally, the output beam is spatially singlemode, with the typical transverse distribution of the second order mode (LP_{11}) of the fiber in the visible range, as shown in inset of Fig. 4. The IR part of the continuum above 1 µm propagates on the single LP_{01} mode whereas the energy between 750 and 1000 nm propagates on both LP_{01} and LP_{11} modes.

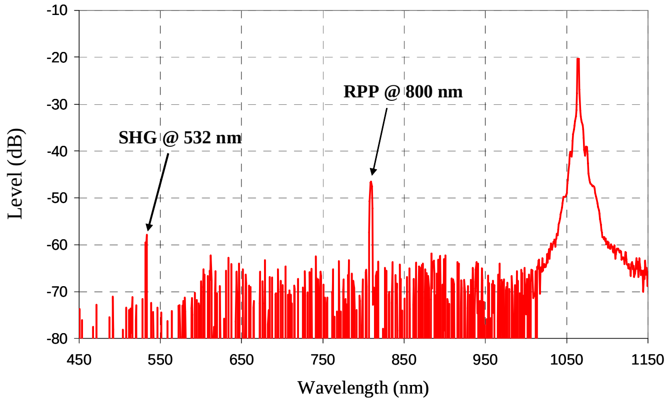

Fig. 3. Spectrum measured at the output end of the microstructured fiber (2 m), showing second harmonic generation at 532 nm from the fundamental wavelength at 1064 nm (RPP = Remaining Pump Power of the microchip laser @ 800 nm). The peak pump power at 1064 nm is 100 W.

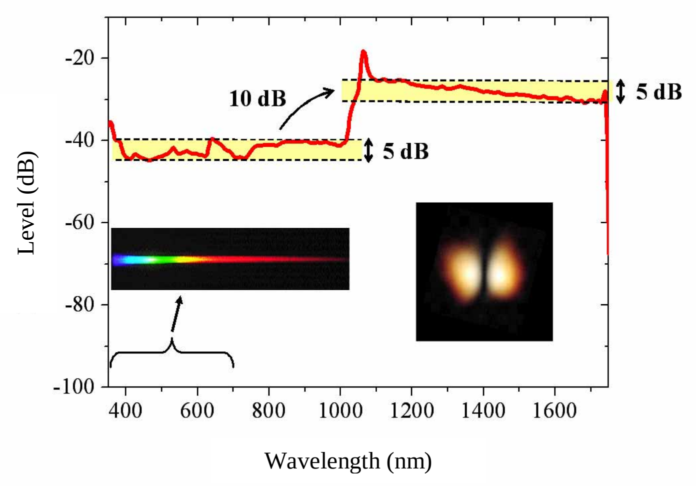

Fig. 4. Spectral broadening measured in visible and infrared ranges (peak pump power at 1064 nm: 6 kW). Inset: fiber output diffracted beam and far field transverse distribution (LP_{11} mode).

5. Analysis of the phenomenon

In order to analyze the experimental results shown on Fig. 4, we computed the parametric gain from the formalism initially developed by Stolen *et al.* in the case of double pumping near the ZDW of the fiber [12]. We applied this formalism to the case of two pump waves (1064 and 532 nm) positioned on both sides and far from the ZDW, for LP_{01} and LP_{11} modes.

The calculated parametric gain is extremely sensitive to the position of the ZDW of the considered transverse mode. When LP_{01} mode (ZDW = 870 nm) is considered, the parametric gain is mainly obtained between the two pump wavelengths. On the contrary, operating on LP_{11} mode (ZDW = 710 nm) permits to create new gain bands, particularly below the pump wavelength at 532 nm, i.e. in large normal dispersion regime. The shift of the ZDW towards shorter wavelengths makes possible phase matched nonlinear processes for visible spectral components and produces light in UV-blue range. Experimentally, the influence of the ZDW position is less significant than in numerical simulations but the experimental work demonstrates that the spectral position of the two pump waves is a crucial point in the spectrum build-up. So the position of the ZDW between the two pump wavelengths determines the shape of the spectrum generated in the fiber but also the conversion efficiency of the nonlinear process. In our case, operating on the second order mode of the fiber has led to a very large broadening, from the UV to the IR, with a low amount of power at 532 nm. In the case of SHG on the fundamental mode, the very low efficiency of this nonlinear process does not permit to induce MI and consequently does not create a large spectral broadening in the visible range.

It is clear that the propagation conditions of the generated second harmonic wave determine the phase matching conditions required for the SHG nonlinear process. This also determines the transverse mode of propagation of the supercontinuum in the visible range. In our case, the SHG is spontaneously created from LP_{01} mode towards LP_{11} mode. This surprising effect was already observed by Osterberg *et al.* [13] in a non microstructured optical fiber. The modal structure of the photoinduced second harmonic light in optical fibers depends on the IR intensity used to pump the material. It seems also that the core profile of the microstructured fiber plays a large role in the propagation of the 532 nm radiation.

The birefringence of the fiber is another important characteristic of the guide for SHG process, and we clearly observed its influence in our experiments. The orientation of the input beam polarization versus the neutral axes of the microstructured fiber permits us to excite LP_{11} mode either with horizontal polarization or with vertical polarization. This determines the polarization of the supercontinuum obtained at the output of the fiber. It is also possible to excite the two orthogonally polarized modes. In this case, these two structures propagate together in the fiber and the supercontinuum observed at the output end exhibits a ring-shaped transverse energy distribution (“white donut”). Nevertheless, the phase matching conditions of nonlinear processes are not identical for the two LP_{11} modes. The spectral width and shape of the generated continuum evolve with the polarization state of the input beam. The maximal enlargement of the spectrum corresponds in our case to a strictly vertically polarized excitation.

A final point is that it is obvious that the second ZDW at 1100 nm plays an important role in the spectral broadening, as it has already been demonstrated in other studies [14-15]. Indeed, the proximity of the pump wavelength at 1064 nm from this second ZDW should favor parametric processes. The change of dispersion sign between the two sides of the ZDW can allow nonlinear phase matched processes and lead in particular to degenerated four wave mixing processes. However, the efficiency of this phenomenon may be limited by the quasi bimodal propagation in this range of wavelength.

6. Conclusion

We have demonstrated ultra wide band supercontinuum generation in a highly nonlinear air-silica microstructured optical fiber, using for the first time SHG process in the fiber. The pump source is a simple subnanosecond microchip laser emitting at 1064 nm. The output beam is singlemode in the visible region and has its spectrum extended over the whole transparency window of silica (350-1750 nm). This spectral broadening is achieved thanks to a modulation instability process in which a wave at 532 nm is involved. This wavelength is created inside the fiber by second harmonic generation from the fundamental frequency of the pump laser.

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This experiment results in the design of a very compact and cost effective white light source, consequently easily usable in many applications. This technique is under patent pending with the French CNRS and opens new perspectives for multi-wavelength pumping of nonlinear microstructured optical fibers.

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