Supercontinuum generation in Ge-doped Y-shaped microstructured tapered fiber

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Abstract. We have investigated the generation of supercontinuum in tapered Y-shaped fibers in the nanosecond pump regime. This fiber used to fabricate the tapers has, in addition, a Ge-doped core which enhances the nonlinearity of the material and the Raman gain. The fiber was pumped at 1064 nm in the ns pump regime (0.6 ns pulses and up to 3.2 kW peak power). The taper had a uniform waist of 0.9 µm diameter and 130 mm length, and the adiabatic transitions were 110 mm long. A flat spectrum spanning from 420 nm to 1870 nm was obtained using a single tapered fiber.

1. Introduction
Supercontinuum (SC) is “the generation of intense ultrafast broadband “white-light” pulses spanning the ultraviolet to the near infrared that arises from the nonlinear interaction and propagation of ultrafast pulses focused into a transparent material” [1]. Supercontinuum generation has been investigated since the 70’s, however, since the manufacture of the first microstructured fiber (MF) in 1996 [2], has emerged a strong interest in this phenomenon because of the great advantages of these fibers have to generate [3-6]. However, although these fibers have more degrees of freedom to adjust their dispersion than conventional fibers, MFs have some limitations that restrict an efficient generation in the visible wavelength range with low pump power. In general, the group index profile in these fibers is the major limitation as it restricts the transfer of energy of solitons (moving toward the long wavelengths) to dispersive waves that are confined to the blue-green zone. One option that may allow the generation to shorter wavelengths is to use a basic scheme with a doubled-frequency Nd:YAG laser emitting at 532 nm and a small-core MF. Microchip passively Q-switched Nd:YAG lasers emitting sub-ns pump pulses meet the requirements for SC generation and are low-cost and compact sources. The core diameter of the MF must be < 1 µm in order to shift the zero-dispersion-wavelength (ZDW) close to 532 nm, in this way, it encourages a generation of SC near this spectral range. Consequently, the pump coupling into the core of the MF is highly critical and unstable. Alternatively, it has been reported the use of conventional fiber tapers or tapers fabricated from MFs [7,8], in which the light is focused into the large core of the untapered fiber. The taper transition couples adiabatically the light into the small core. However, high energy ns pulses at 532 nm easily damage the core of the thin fiber taper, which limits the extension of the SC and the power spectral density.

In this way, several approaches for visible light generation using inexpensive cuasicontinuum lasers emitting around 1064 nm have been reported. Some of them are based on multi-stage
arrangements with decreasing ZDW [9-11], a few meters long tapered MF fabricated in a fiber drawing tower [12] or using an MF with conveniently designed dispersion and group index [13].

We report experimental results on SC generation in a taper fabricated from a Ge-doped Y-shape microstructured fiber. The taper was made with long transitions. The first ZDW of the taper waist was shifted down to 647 nm. Because of the long transitions, this single taper behaves as a two-stage arrangement, where the ZDW decreasing transition generates spectral components near the first ZDW of the taper waist, which subsequently extends the spectrum towards even shorter wavelengths. With similar pump conditions than in [5], a SC spectrum spanning from 420 nm to 1850 nm was generated. To our acknowledgment, it is the widest SC generated in a single microstructured fiber taper in the ns pump regime using a 1064 nm pump source.

These tapered fibers are particularly efficient in the generation of a broadband supercontinuum spectrum, at both short and large wavelengths, thanks to a combination of two factors: first, the special dispersion properties along the transitions and the uniform waist and, second, a reduced radiation loss at long wavelength, due to the large air-holes [14]. On the one hand, as the diameter of the fiber decreases along the transitions, the ZDW moves towards shorter wavelengths and, on the other hand, the uniform waist exhibits two ZDWs at 647 nm and 1127 nm.

Thus an efficient cascaded four-wave mixing mechanism is enabled, which fills the short and large wavelength parts of the spectrum. At the same time, the reduced radiation loss prevents the attenuation of solitons at large wavelengths and preserves the Raman self frequency shift of solitons mechanism, enabling the extension of the spectrum to longer wavelengths. In addition, the Ge doping of the core increases the nonlinear refractive index [11] and the Raman gain [15], and it reduces the modal effective area, thus enhancing nonlinear effects. Additionally, it allows, if necessary, collapsing the air holes while maintaining guidance, and it facilitates low-loss splicing to standard single mode fibers.

By tapering the MF, the interaction length required for SC generation can be reduced from several meters to some tens of centimeters. As an example, in [13] the short wavelength edge of the SC was extended down to 400 nm using a 10 m long MF, while the length of the taper used for the results reported here was ~35 cm long. Owing to the large air holes of the Y-shape fiber, the fabrication of the taper did not require tight control of the pressure within the holes during the taper fabrication.

This kind of tapers have a further peculiarity, as the core diameter at the taper waist is submicrometric, thus the fields overlap strongly with the big holes. This special feature, in conjunction with the capability of the taper to generate the SC, could eventually be exploited for the design of monolithic and compact gas sensors or gas cells where the taper generates the broadband light source and also allows strong light interaction with the gas filling the holes.

2. Fabrication

The microstructured fiber used for the fabrication of the tapers is shown in figure 1 (a). This is described in detail in [5,16]. It is a solid-core fiber with Y-shaped cross section and three large air holes in the cladding. Three narrow and long bridges sustain the core at the centre of the fiber. The diameter of the core was ~5.5 μm, the diameter of the air-hole microstructure was 65 μm and the outer diameter of the fiber was 102 μm. The central region of the core of about 6.5 μm² area was Ge-doped (NA = 0.29). The fiber is few-moded at visible wavelengths.

The fibers were tapered using a traveling-flame elongation method [8]. The exposure temperature was controlled by placing the taper area to stretch in some areas of the oxidation cone and adjusting the gas mixture (butane/oxygen) of the flame. In general, when tapering an MF, surface tension causes collapse of the air holes as the fiber is heated. As a consequence, the air-filling fraction decreases, the effective area increases, and the nonlinear parameter, γ, becomes smaller. Additionally, the confinement loss at long wavelengths increases [14]. The technique that is mostly followed to counteract the air hole collapse consists on applying a pressure of an inert gas into the holes while the fiber is being tapered [8,17]. The pressure required depends inversely on the diameter of the holes.
Typical pressure values for tapering conventional MFs are about 6-7 bar. One advantage of using the Y-shaped fiber (with very large air holes) for tapering is that lower pressure values are required (< 1 bar).

Several tapers with similar construction features were made. The resulting tapers had a uniform waist of 0.9 µm diameter and 130 mm length, and the adiabatic transitions were 110 mm long. SEM image of one taper are show in figure 1 (b). An excess pressure of just 0.5 bar in the holes was enough to preserve the very large air filling fraction of the original fiber in the taper. We also fabricated tapers without pressurizing the holes and, a rather small the hole collapse was observed. However we did observed that those tapers did not show significant higher transmission losses.

The figure 1 (c) show the intensity distribution of the fundamental mode in the core of the taper waist calculated with the package SMT [18]. The field is confined mainly in the central core of the device. The Ge-doped core of the original fiber, and therefore, at the core of taper, helps to confine the energy in it.

![Figure 1](image)

**Figure 1.** Scanning electron images of (a) the fiber used to fabricate the tapers, (b) the cross section of the taper waist and (c) intensity distribution of the fundamental mode in the core of the taper waist calculated with the package SMT (the inner triangle indicates the area doped with germanium).

### 3. Experimental results

Several experiments were carried out to evaluate the contributions of the different sections of the device, i.e., the transitions and the uniform section. First, we studied the SC generation at the taper's out by varying the pump laser power and, second, we studied the SC generation along the taper to a fixed value of pumping power. We used a compact Q-switched Nd:YAG microchip laser emitting at 1064 nm (0.6 ns duration pulses, 20 kHz repetition rate) as pump source. The maximum average output power of the laser is 160 mW, corresponding to a peak power of 13 kW, approximately. The pump was launched into the fiber taper at the beginning of the transition (the dimensions are those of the initial fiber) which allows achieving a large pump coupling efficiency. A × 16 aspheric lens was used to focus the beam into the core.

Figure 2 (a) shows the results of the first experiments. It show some SC spectra recorded at different pump pulse peak power levels: 0.9 kW, 1.1 kW, 1.4 kW, 1.8 kW, 3.2 kW. The spectral resolution was 5 nm. At low pump power, three bands can be observed along with the pump signal. These bands are centered at 1053 nm, 1075 nm and 1113 nm. As the pump power was increased, the intensity of the bands increased and, at 1.4 kW of peak power, the spectral broadening is already considerable. As the pump power level was increased further, the spectrum exhibits a continuous broadening towards both sides of the pump wavelength. At the highest pump power (3.2 kW peak power), the spectrum spans over more than 1400 nm, from 420 nm to 1850 nm. The spectrum generated at the highest pump power is remarkably flat, from 850 nm to 1500 nm the intensity variation is within 3 dB. The spectrums up to 1750 nm (solid line) were recorded with an OSA ANDO AQ-6315A. The long wavelength side of the spectrum (dashed line) was measured with an OSA.
Yokogawa AQ-6375, which has no order-sorting filters. Thus, a 1.3 µm cut-on long pass filter was used to prevent multi-order interference in the measurement.

The top of the figure 2 (a) shows some images of the output far-field pattern unfiltered or passed through visible bandpass filters, where no evidences of higher order modes can be observed. At the highest pump power level, the output from the tapered fiber was essentially white. The continuum was observed to be generated in the fundamental mode.

A further 10% increase in pump power (up to 3.5 kW peak power, approximately) caused the damage of the taper at the end of the taper waist. The pump power level was kept constant and, after few minutes, the taper resulted damaged again but now at the end of the first transition, i.e. at the beginning of the uniform waist. In both points were observed scattered light. The scattered light at the last point contains red spectral components, which indicates that a significant contribution to the resulting SC spectrum is generated in the taper transition. Another important consequence of the spectral broadening at the input transition is that the signal entering the taper waist, which acts as the pump for the nonlinear effects in this taper section, is spectrally very broad and it does not only contain the 1064 nm signal from the pump laser. To confirm that the long transitions contribute significantly to spectral broadening, a second taper with similar structure was fabricated. Figure 2 (b) shows the results of this second experiment. It shows the SC output spectrum at different test points of the taper: (A) at the beginning of the input transition, (B) at the end of the input transition, (C) and at the end of the taper’s output. Although the pump power was lower than in the previous experiment (2.4 kW), a broad spectrum was recorded at the end of the input transition and the end of the uniform waist.

![Image of far-field pattern and SC output spectrum](image)

**Figure 2.** (a) (top) Far-field pattern of the output beam unfiltered and filtered with different visible bandpass filters, and (bottom) SC output spectrum for different pump pulse peak power levels: 0.9 kW, 1.1 kW, 1.4 kW, 1.8 kW, 3.2 kW. (b) (top) Scheme of the taper with test points, and (bottom) SC output spectrum at different test points of the taper. Pulse peak power: 2.4 kW.

4. Discussion

The source-model technique was used to calculate the basic theoretical guiding properties [18]. This approach allows modeling fibers with arbitrary refractive-index distributions, thus, the real refractive index profile was taken into account. The accuracy of the simulations performed with this tool has been evaluated in previous studies [19]. This was compared with various numerical methods. According to the conclusions, the differences between this approach and tighter parameter depend on
the method used to compare and to contrast. For example, in the case of ZDW fundamental mode, there is a difference of 2% of the value obtained with the SMT and obtained with the LFM robust method. Thus, the SMT method allows approximate properly the experimental ZDW’s of our fibers and tapers.

Figure 3 (a) shows the dispersion as a function of wavelength of the fundamental mode of the untapered fiber (solid line) and the taper waist (dashed line). In the case of the untapered fiber, the first ZDW is 1195 nm, while the second ZDW is out of the calculation range. As the scale of the fiber is reduced, both first and second ZDW shift to shorter wavelengths. The dispersion of the taper waist shows two zero dispersion wavelengths centered at 647 nm and 1127 nm, being the dispersion anomalous at the wavelength range between the two ZDWs. Figure 3 (b) shows the evolution of the first ZDW along the taper transition. The dispersion at the pump wavelength is anomalous in most of the transition length, with the exception of the first few mm.

The process of SC generation is initiated by MI, as it is shown at low pump power, where a pair of symmetrically-located peaks appears on both sides of the pump. Modulation instability (MI) is a nonlinear effect that occurs temporally as a breakup of a CW or quasi-CW radiation into a train of ultrashort pulses, and spectrally as two symmetrically-located peaks on both sides of the pump. A third band located at 1113 nm corresponds to stimulated Raman scattering (SRS) generated by the pump, probably, along the section of the taper with normal dispersion. Notice that the generation of SRS is enhanced by the presence of GeO\textsubscript{2} in the fiber [20]. The ZDW decreasing along the transition allows the four-wave mixing (FWM) phase-matching condition to be satisfied for a wide range of wavelengths. A cascaded FWM process along the taper transition is enabled, which would extend the spectrum on either side of the pump wavelength. At a given point of the transition, the spectral components generated in the normal dispersion regime allow shorter wavelengths to be generated via FWM in the next section of the transition. In particular, the extension towards the visible reaches the red wavelengths. Simultaneously, Raman self-frequency shifted solitons (SSFS) propagating in the taper transition will contribute to the generation towards longer wavelengths.

The broadband light generated in the taper transition pumps the uniform taper waist. The dispersion in the taper waist for many of the spectral components generated in the transition is anomalous, i.e. those laying between the two ZDWs. As shown in figure 3 (a), at high pump power levels the taper transition generates red components, which are close to the first ZDW of the taper waist. It is also expected that the beam entering the taper waist would contain components close to its second ZDW. Therefore, a multi-FWM process is enabled in the taper waist, which extends the spectrum towards even shorter wavelengths, as it has been observed previously in multiple tapers configurations [11].
We believe that the contribution to the spectral broadening of SSFS generated by the pump in the taper waist is small, since the wavelength range where solitons can be generated, i.e. between the pump and the second ZDW, is quite narrow.

5. Conclusions
We have reported experimental results on the SC generation in a taper fabricated from a Ge-doped Y-shape fiber. The taper was pumped at 1064 nm wavelength in the quasi-continuum pump regime (ns) using a Q-switched microchip laser. The taper can be understood as a multi-stage configuration formed by the taper transitions, where the ZDW changes continuously, and the taper waist. The spectral components generated along the input taper transition act also as pump the taper waist, whose dispersion is anomalous for many of them. Therefore, a multi-FWM process is enabled in the taper waist. At a pump pulse peak power of 3.2 kW, a broad spectrum is reported. The spectrum extends from 420 nm to 1870 nm when measured at $-20$ dB, and from 850 nm to 1500 nm when measured at $-3$ dB.

6. References
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