Supercontinuum generation in submicron fibre waveguides

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Abstract: Submicron-diameter tapered fibres and photonic crystal fibre cores, both of which are silica-air waveguides with low dispersion at 532 nm, were made using a conventional tapering process. In just cm of either waveguide, ns pulses from a low-power 532-nm microchip laser generated a single-mode supercontinuum broad enough to fill the visible spectrum without spreading far beyond it.

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1. Introduction

The generation of spectrally-broad single-mode supercontinuum (SC) light in photonic crystal fibre (PCF) [1] or tapered conventional fibre [2] is well documented. In both cases, light is confined to a silica waveguide surrounded substantially or entirely by air. The large refractive index step allows light to be concentrated into a small area. The strong waveguide dispersion shifts the zero dispersion wavelength (ZDW) to wavelengths much shorter than 1270 nm (the ZDW of bulk silica). The first results [1,2] were for waveguide diameters of ~2 µm with the ZDW near 800 nm, generating two-octave SC with fs pulses from Ti:sapphire lasers. Short pulses raise the peak intensity for a given average power, enhancing the effective nonlinearity. Mere cm of fibre were enough to achieve spectacular broadening.

Low dispersion is the key to efficient broadening, as it enables single-mode phase-matching of the nonlinear processes that broaden the spectrum. Optimising dispersion relaxes the need for high intensity, allowing SC generation for larger cores and/or longer pulses [3]. This approach is particularly effective for the wavelengths of Nd lasers (eg 1064 nm for Nd:YAG) where material dispersion is not large, giving greater scope for modifying waveguide dispersion to tailor net dispersion. Hence single-mode SC can be generated from the ns pulses of a Q-switched Nd:YAG "microchip" laser (a compact and low-cost source) in 20 m of PCF with a core diameter as big as 5 µm [4]. Tapered fibres have fewer degrees of freedom and are short, but a few cm can generate broad SC from microchip laser radiation if the dispersion spectrum is flattened by immersing the taper in a suitable liquid [5].

We report the first exploration of SC generation in this hitherto-unexplored dispersion regime. Submicron-diameter fibre waveguides were made by two alternative methods. In the first, conventional fibres were tapered to reduce the entire fibre to submicron size (drawdown ratio ~250:1). In the second, PCFs were tapered to reduce the fibre’s core to submicron size (drawdown ratio just ~6:1). The transitions simplified input and output coupling in both cases. Standard tapering techniques were effective for making submicron taper waists, as well as the first guiding submicron-pitch PCFs. We investigated the broadening of ns pulses emitted at 532 nm by a frequency-doubled microchip laser (JDSU Nanogreen, 0.6 ns pulses, repetition rate 6.33 kHz, ≤1 kW peak power coupled into fibre). Single-mode SC light spanning (yet largely confined to) the visible spectrum down to 400 nm was generated in as little as 20 mm of submicron fibre.

![Fig. 1. (a) (1060 kB) Evolution of the calculated dispersion spectra of taper waists as the diameter (labelled) decreases. The straight lines mark zero dispersion and 532 nm wavelength. (b) A schematic tapered fibre, showing the waist connected to untapered fibre by transitions, and the spread of the mode to fill the fibre in the narrow waist.](image)
2. Submicron tapered fibres

Tapering a fibre involves heating and stretching it to form a narrow waist connected to untapered fibre by taper transitions, Fig. 1(b). If the transitions are gradual, light propagating along the fibre suffers very little loss. A "flame brush" that travels to and fro along the fibre produces waists of uniform and predictable diameter [7]. In our variant the travel distance changes as tapering proceeds, giving control of waist length independently of transition length [8]. Otherwise, long waists would have impractically long transitions.

The fabrication of submicron-diameter taper waists was recently described by Tong et al [9], though it was first reported some years ago [10]. Unlike [10], Tong et al used a two-stage process involving a heated sapphire tip. This extra step is unnecessary: we reported at OFC in February [11] that conventional tapering can produce waists of 300 nm diameter with 10× lower loss. The properties of typical samples made using Corning SMF-28 fibre are given in Table 1, showing their much lower loss (now over two orders of magnitude less per mm despite including the losses of the transitions) and longer waists.

Table 1. Typical loss per unit waist length, for our taper waists with the specified diameter and length

| diameter, nm | length, mm | wavelength, nm | loss, dB/mm | loss from [9], dB/mm |
|-------------|------------|---------------|------------|---------------------|
| 950         | 90         | 1550          | 0.0014     | 0.21                |
| 890         | 90         | 1550          | 0.0017     | 0.29                |
| 360         | 30         | 633           | 0.0083     | 0.21                |
| 280         | 30         | 633           | 0.011      | 0.38                |

Loss was measured by simply recording transmission before and after tapering. For single-mode measurements at wavelengths where SMF-28 is multimode, a section of fibre was tapered (in situ; no splices needed) to make it locally single-mode. Any light in higher modes spreads into the cladding and is absorbed by index-matching gel placed around the fibre [12]. A low drawdown ratio of ~3:1 was enough to ensure only fundamental-mode excitation at 532 nm in submicron waists subsequently made downstream of this mode filter.

Control of waist diameter is key to our nonlinear experiments. The predictability of the variable flame-brush technique [8] was improved by explicitly modelling what happens when a flame passes at speed \( u \) along a fibre stretched at rate \( v \). Conservation of volume leads to the ratio by which the diameter \( d_n \) of the waist is reduced by a single pass of the flame:

\[
\frac{d_{o}}{d_{n}} = \left[ \frac{1 - v/2u}{1 + v/2u} \right]^{1/2}.
\]  

(1)

With this refinement, we can produce waists of specified diameter despite the high drawdown ratios involved (up to 450:1). For example, Fig. 2 is an SEM image of a waist of nominal diameter 620 nm, matching the measured value to within the accuracy of the SEM.

![SEM image of a taper waist with a nominal diameter of 620 nm, as predicted by Eq. 1.](image)

3. SC generation in submicron tapered fibres

Light from the 532 nm laser was coupled into the fibre via a variable attenuator. Operation of the mode-filter was verified by inspecting the output far-field pattern at low power, Fig. 3(a). Then submicron waists were formed while monitoring loss, which in all cases we describe
was less than 0.2 dB. The input power was increased and the output spectrum measured using an Ando AQ6315B optical spectrum analyser. Where necessary, power measurements were made with a broadband optical power meter.

The dispersion is zero or flattened at 532 nm in waists with diameters around 900 or 500 nm respectively, Fig. 1(a). This facilitates SC generation despite the short length and low peak power. Typical output spectra are plotted in Fig. 4. For both diameters, the SC spectrum fills the visible range but extends little beyond it. However, only 20 mm of 510-nm fibre (and half the power) was needed to fill the visible spectrum, compared with 90 mm of 920-nm fibre. Fig. 5 maps the evolution of the spectrum with power for the 920 nm waist in SMF-28. SC generation has apparently not saturated: broader spectra could be expected for higher powers or a longer waist. (This is analogous to the 1-m PCF in [4], in contrast to the 20-m PCF where SC generation had saturated and increased power or length made little difference.)

The output was white despite the persistence of unconverted pump light. It remained in the fundamental mode; no multimode coupling was observed. Typical far-field patterns unfiltered or passed through bandpass filters show no evidence of higher-order modes, Fig. 3, in contrast to [13]. SC spectra from two samples, otherwise identical except one is made from Nufern 630-HP fibre (cutoff wavelength 545 nm) instead of Corning SMF-28 (cutoff wavelength ~1200 nm), are plotted in Fig. 4(a). Despite the difference between the fibres’ cores, and
particularly that the Nufern fibre is single-mode near the pump wavelength, the spectra are virtually indistinguishable. This is further confirmation that the processes are single-mode.

4. Submicron PCF cores

Tapered fibres have received less attention for SC generation than PCFs, probably because they are short and need to be carefully packaged. Nevertheless input and output coupling in tapers is simple for any waist diameter, whereas for PCFs it becomes ever more difficult as core size decreases. Furthermore PCFs with submicron pitch are hard to make, especially since the air-filling fraction must be high for light to be well-confined to the core. Hence there have been no reports of SC generation in submicron PCF cores to date, despite the advantages (e.g., length and simplified packaging) they otherwise have over tapered conventional fibres.

To combine some of the advantages of both waveguide structures, we used our tapering rig to make sections of PCF with submicron cores from a 3.1-µm core PCF (Fig. 6) supplied by BlazePhotonics [14]. Note the contrast between our treatments of conventional fibres and PCFs, which were tapered so that the whole of the former but just the core of the latter was reduced to submicron size: the outer diameter of the tapered PCF waist was as big as ~30 µm. Although our PCF did not have the conventional guiding core of Liu et al’s special tapered PCF [15], coupling to a 3.1 µm core is straightforward and the taper transitions form low-loss interfaces to the submicron core, Fig. 7(a). Loss measurements were less reliable than for conventional fibre, as a mode-filter would need similar dimensions to the submicron sample itself. However, ~0.5 dB tapering loss was measured after optimising coupling to the fundamental mode, giving a transition loss of ~0.25 dB. We believe much of this represents the losses of remaining higher-order modes.

Tapering is in principle better at making nanostructured PCF sections than fibre drawing on a tower. To minimise hole collapse under surface tension, an ideal process would draw the whole fibre structure at maximum stress. Fibre drawing is far from this ideal because nearly the same force is applied along the neck-down region, so the stress in its wider parts is well below the maximum, Fig. 7(b). In contrast, tapering applies a constant stress, governed by the viscosity profile and elongation rate but not fibre diameter [16]. If stress is maximised without breaking the fibre, tapering approaches the ideal process. It can be shown that hole collapse is less in tapering than drawing (if both are optimised) by a factor equal to the drawdown ratio, so tapering is inherently 6× better at reducing our PCF pitch from ~3 µm to 0.5 µm.
Hence by tapering "fast-and-cold", i.e., with relatively high elongation rate and low flame temperature for high drawing stress, the microstructure in 90-mm lengths of the PCF could be preserved while reducing the core diameter to as little as 300 nm. Their dispersion spectra were not calculated, but should resemble those of conventional taper waists of comparable size. SEM images for core diameters of 700 nm and 500 nm are shown in Fig. 6, and typical SC spectra for 90-mm lengths with these diameters using the 532 nm laser are shown in Fig. 8. The spectra are similar to those of the conventional tapers, though the one for the 500-nm diameter core spreads further into the infrared.

5. Discussion and conclusion

This is the first report of SC generation in air-silica fibre waveguides of submicron diameter, and indeed of any form of optical guidance along PCFs with submicron pitch. We were able to explore a dispersion regime well-matched to frequency-doubled microchip lasers. Previous reports of SC generation with 532 nm light (e.g., [13]) relied on higher-order modes in bigger cores for nonlinear phase-matching, whereas in submicron waveguides phase-matching is possible in the fundamental mode. The physics of the nonlinear broadening is expected to be as discussed in [4] but applied to shorter wavelengths. The resulting single-mode SC filled the visible spectrum while extending little beyond it. This is significant for visible applications, as any infrared light generated would be wasted. The resulting compact visible source could find applications in optical coherence tomography, spectroscopy and optical device measurement.

We also described important developments in the fabrication of the submicron waveguides themselves. For taper waists, use of a sapphire tip was presented as an enabling innovation in the well-publicised work by Tong et al. [9] but is nevertheless a cumbersome extra process step that yielded only half the complete taper structure of Fig. 1(b): one transition was missing, and further steps had to be taken to couple light in and out. However, the extra step is unnecessary. Conventional tapering is actually superior, yielding complete structures with transitions at both ends and uniform waists up to 100 mm long or as little as 300 nm in diameter. Made by machine with less human intervention, losses per mm can be over two orders of magnitude lower than [9].

We used tapering to make PCFs of submicron core diameter and pitch, and described the guidance of light in such structures for the first time. The apparent inability of anyone to make them by standard fibre drawing supports our view that tapering is inherently better at preserving nanostructure in PCFs. The disadvantage of tapering is that only short lengths are produced. However, some applications only need cm lengths, and for these tapering should be the best way to make nanostructured PCFs.

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