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Observation of the Developing Optical Continuum Along a Nonlinear Waveguide

John D. Mills[1], Tipsuda Chaipiboonwong[1], Martin D. B. Charlton[2,3], Majd. E. Zoorob[3], Caterina Netti[3], Jeremy J. Baumberg[3,4] and William S. Brocklesby[1]

[1] Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK

[2] School of Electronics and Computer Science, University of Southampton, SO17 1BJ, UK

[3] Mesophotonics Ltd, Chilworth Science Park, Southampton, SO16 7NP, UK

[4] Dept of Physics and Astronomy, University Of Southampton, SO17 1BJ, UK

We describe the first non-destructive measurement of the evolution of an optical continuum as a function of distance along a nonlinear waveguide. Spectral mapping is achieved on a sub-wavelength scale by utilizing near-field microscopy to probe the waveguide's evanescent field. The large-scale optical broadening along the waveguide is compared to theory for various pulse energies. Smaller-scale measurements are made both along and across the waveguide to reveal spectral variations not seen before by other techniques.

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Supercontinuum generation in optical waveguides by nonlinear propagation of ultrafast laser pulses provides an important new source of electromagnetic radiation, with very broad spectral bandwidth on femtosecond timescales. The supercontinuum can span more than an octave in frequency opening up the possibility of many new applications in physics[i,ii,iii]. However, the understanding of the process of generating supercontinuum along the length of a waveguide is difficult because of the large number of contributing effects such as group velocity dispersion, self-phase modulation, four-wave mixing and stimulated Raman scattering. Up to now, all study of continuum sources has been via their output only, but this information is necessarily limited[iv,v]. The recent development of supercontinuum rib-waveguide devices[vi], which allow access to the evanescent optical field makes possible a new insight into the generation process. Using a near-field scanning optical microscope (NSOM), the spectrum can be sampled along the length of the device via its evanescent field while the light is actually being generated, allowing observation of its evolution in a manner previously impossible. Here we present the first NSOM measurements of evolving spectra along such a device, concentrating initially on the lower power regime - only a limited continuum bandwidth rather than the full supercontinuum.

The waveguide used in these experiments was selected from a set of rib waveguides on a Mesophotonics Ltd. supercontinuum generation chip[vii]. It consisted of a Ta_2O_5 stripe of length 6mm, width 4μm, and height 0.5μm, on a layer of SiO_2, grown on a silicon wafer. Laser pulses of duration 86fs, wavelength 800nm at a repetition-rate of 76MHz were focused into the end of the waveguide via an aspheric lens (0.68 NA) with pulse energies ranging 0.8nJ to 2.1nJ. The evanescent field which extended above the guide into the air had a measured decay length of 70nm. The light was sampled using an uncoated NSOM probe of ~100nm tip diameter held at a fixed distance of 20nm from the guide surface by shear-force feedback[viii]. The probe, which was fabricated by tapering a length of single-mode fiber with a standard pipette puller, could be moved to any lateral position along or across the guide by a combination of coarse manual adjustment and piezoelectric actuators. The light collected by the probe's tip passed along its fiber to a high-resolution CCD-based spectrometer. The spectrometer in turn could be conveniently switched to measure the output from the waveguide itself via a collection objective and fiber, without disturbing the experiment.

Figures 1(a) and 1(b) compare the spectrum of the continuum as it evolved along the length of the waveguide for input pulse energies of 2.1nJ and 0.8nJ respectively. The spectra shown were obtained along the central axis of the guide by sampling the local spectrum via the evanescent field at regular intervals from 0.5mm to 5.5mm. The laser output spectrum itself, having a FWHM of 11nm is included in the figures at position 0mm for reference. Additionally, the waveguide outputs are shown at position 6.0mm. The build-up of the continuum along the waveguide in each case is clearly visible with as expected, a greater rate of development for the higher energy pulses. The direct visualization of continuum growth in this manner opens up the tantalizing possibility of pin-pointing exactly where individual wavelength components initiate their growth along the length of the rib, and at what rate they develop. The technology will offer an opportunity to enhance theoretical understanding of the complex mechanisms leading to continuum and supercontinuum generation. In a theoretical system where the nonlinear effects are integrated along the device, with each nonlinear generation process relying on the generation in the previous section, the ability to correlate physical mechanisms to their exact spatial location will be of great advantage. Interestingly, the guide output measurements, which up to now have been the only means of characterizing these devices, do not show the detailed spectral intensity variation due to mode beating recorded by the evanescent sampling. This is directly attributed to the high spatial resolution capability of NSOM. In the case of the sample presented here, the local spectrum due to mode beating varies rapidly both across the guide and over lengths of ~5μm along the guide, so is averaged out in any measurement with poor spatial resolution.

Figure 2 shows more clearly the rate of growth of the spectra as a function of distance along the waveguide. Here, the $1/e^2$ widths of the spectra shown in Figure 1 are displayed along with an additional data set using an intermediate pulse energy of 1.4nJ. The measured widths in each case are compared to results from theoretical calculations based upon a simple split-step beam propagation model[ix]. In the calculation, only the input pulse energy is varied in line with the experimental variation to produce the different traces. With constant launch efficiency, the modal diameter which produced the best fit was 1.85μm. Clearly the fit is not good for all energies at all positions, which may be a consequence of the multimode nature of the guide or a need for modification of the theory. Most notably, the theory does not appear to accommodate the high rate of spectral growth measured for all pulse energies at the front end of the waveguide. The level of deviation is interesting because of the low energy regime used for these experiments where theory is least complicated. We are currently planning to extend the NSOM measurements to the regime of supercontinuum where the broadening mechanisms are much less well characterized.

Figure 3 gives an example of how the spectrum of the generated light is observed to evolve on a much smaller length scale. With the NSOM probe positioned 3mm from the input facet along the waveguide's central axis, spectra were collected at 100nm intervals (about the resolution of the probe) along an overall length of 2μm in a direction along the guide. In this figure the spectrum is seen to broaden and narrow on a length scale of ~400nm, which is approximately the wavelength of the light in the guide and probably a consequence of modal beating. The spatial variation was repeatable over periods of ~1 hour, showing that the laser intensity and coupling into the guide was extremely stable, and did not contribute to the variations observed. Across the guide, spectral variation is also considerable. With steps at 500nm intervals, Figure 4 displays spectra sampled in a direction orthogonal to the propagating light. Since NSOM has a capability which allows it to simultaneously map the surface topography of a sample, we can correlate precisely the lateral position of each acquired spectra to its position on the waveguide. Figure 4(a) shows the position of the tip as it moves up and over the rib of the guide, whilst the corresponding spectra sampled at the various positions are displayed at the given points in Figure 4(b). As expected, the considerable variations seen in the localized measurements average to a normal mode profile as can be seen in Figure 4(c), by integrating across all wavelengths at each lateral position.

In summary, we have described the first non-destructive measurements of the evolution of an optical continuum along a nonlinear waveguide for various input pulse energies and compared the growth of the spectra to standard theory. We have also demonstrated the high-resolution capability of the NSOM measuring technique, by showing the considerable localized variation in the spectra of the developing continuum that exists both along and across the guide on a sub-wavelength scale. The capacity to visualize the development of nonlinear processes along and across waveguide devices with NSOM will not only enable a much better understanding of the important design properties of such devices, but also assist in the development of theory. This technique should also lend itself to more complex analysis of the nonlinear process, such as localized phase measurement or sub-wavelength-scale FROG analysis of the evolving pulse. We are currently planning to extend these studies to include guides with greater confinement in order to simplify the modal structure and to seek understanding of the evolution of spectra in the regime of supercontinuum.

Figure Captions

Fig. 1. NSOM evanescent field spectral measurements of the continuum evolution along a 6mm Ta_2O_5 waveguide for input pulse energies (a) 2.1nJ and (b) 0.8nJ. For reference, the incident laser spectrum is included in each case at 0mm, whilst the waveguide output is given at 6.0mm.

Fig. 2. Comparison of the widths of the evolving spectra along the length of the waveguide with theory. Data shown in Figure 1 is displayed again along with a further data set with intermediate pulse energy 1.4nJ.

Fig. 3. An example of how the continuum is observed to evolve on a much smaller length-scale. Here, the spectrum is seen to broaden and narrow on a length scale of ~400nm, which is approximately the wavelength of the light in the guide.

Fig. 4. Spectra sampled along a direction orthogonal to the propagating light. 4(a) shows the NSOM-derived cross-sectional topography of the rib waveguide, 4(b) the corresponding spectra sampled at the various positions and 4(c) the integrated cross-sectional mode profile.

Figure 1

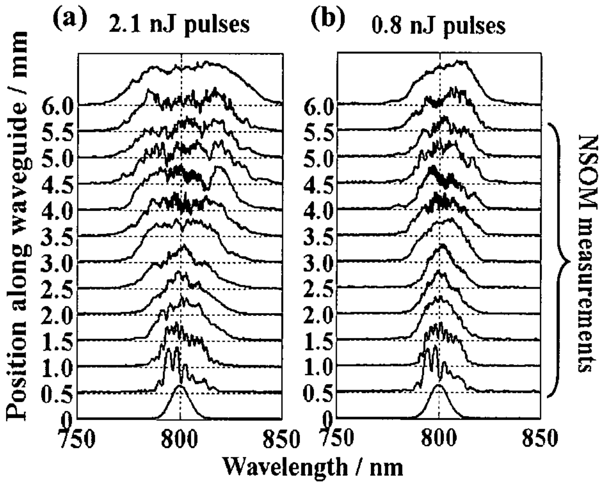

(a) 2.1 nJ pulses
(b) 0.8 nJ pulses
Position along waveguide / mm
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
750
800
850
Wavelength / nm
NSOM measurements

Figure 2

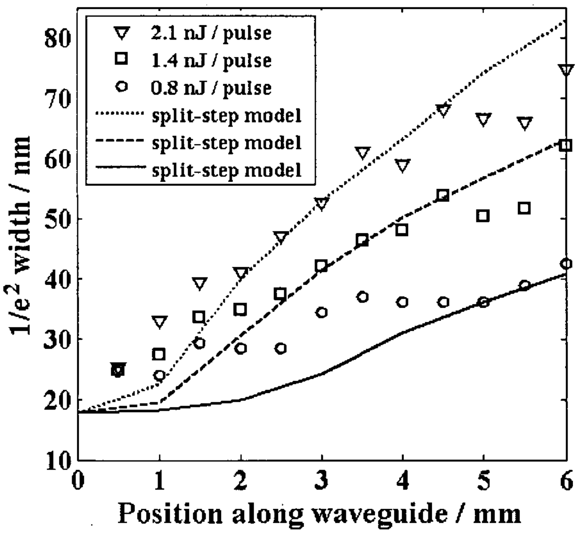

▽ 2.1 nJ / pulse
□ 1.4 nJ / pulse
○ 0.8 nJ / pulse
split-step model
split-step model
split-step model
1/e^2 width / nm
Position along waveguide / mm
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6

Figure 3

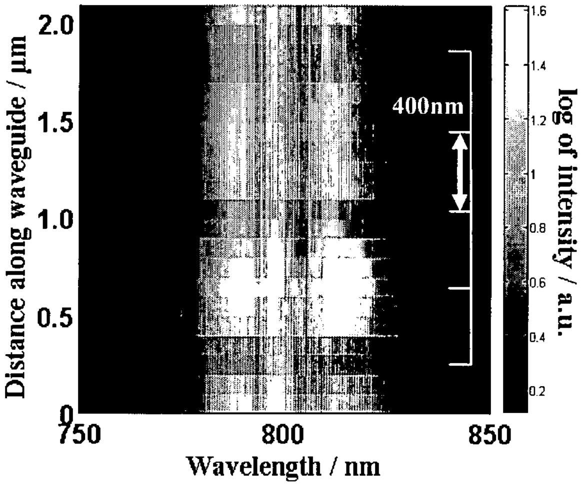
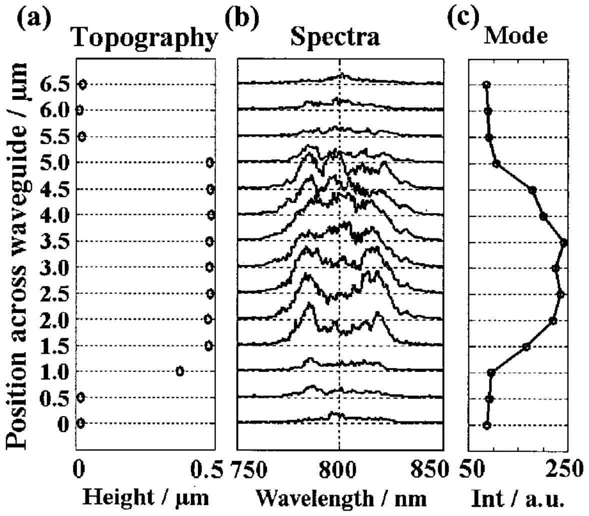

Distance along waveguide / µm
2.0
1.5
1.0
0.5
0
750
800
850
Wavelength / nm
400nm
log of intensity / a.u.
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2

Figure 4


(a)
Topography
(b)
Spectra
(c)
Mode
Position across waveguide / µm
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0
0.5
Height / µm
750
800
850
Wavelength / nm
50
250
Int / a.u.

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