Multiplex frequency conversion of unamplified 30-fs Ti: sapphire laser pulses by an array of waveguiding wires in a random-hole microstructure fiber

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Abstract: An array of fused silica waveguiding channels with randomly distributed transverse sizes in a disordered microstructure fiber is shown to allow a highly efficient broadly tunable frequency conversion of low-energy ultrashort laser pulses. Dispersion can be switched in such waveguide arrays by coupling the pump field into waveguiding wires with different diameters. Microstructure-fiber-integrated random arrays of waveguides with diameters ranging from 0.6 up to 1.5 µm can frequency-convert unamplified subnanojoule Ti: sapphire laser pulses with an initial duration of 30 fs to any wavelength within a broad spectral range from 400 up to 700 nm, suggesting interesting fiber-optic strategies for multiplex frequency conversion and sensing.

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References and links
1. Introduction

Microstructure (MS) fibers [1] offer a remarkable variety of guided-wave solutions for nonlinear optics and ultrafast photonics. The MS-fiber architecture allows, in particular, experimental investigation of temporal evolution and nonlinear-optical transformations of ultrashort laser pulses in ultrathin waveguiding channels, whose diameter can be made less than the radiation wavelength [2-10]. Multiple submicron waveguide channels in MS fibers have been shown to allow multiplex frequency conversion of ultralow-power Ti:sapphire [2,3] and Cr:forsterite [10] laser pulses. Delicately fabricated subwavelength-core MS fibers with a precisely controlled dispersion provide means to observe supercontinuum generation with unprecedentedly low powers of laser pulses, as well as to finely tune and tailor supercontinuum generation [8,9]. These experiments suggest new practical solutions for efficient frequency conversion of ultrashort pulses and raise several fundamental issues related to the limiting efficiencies of waveguide-enhanced nonlinear-optical processes and interesting nonlinear-optical phenomena controlled by a trade-off between diffraction and step-index field confinement in submicron waveguide wires [11,12].

In this work, we demonstrate that a random array of fused silica waveguiding wires with diameters ranging from 0.6 to 1.5 µm in an MS fiber can provide a high efficiency of broadband frequency conversion of unamplified ultrashort laser pulses. MS fibers with a random array of holes have been earlier used for gas-phase sensing [13]. Here, we focus on nonlinear-optical applications of this type of MS fibers, requiring a more careful design of the
network of waveguiding channels, reducing the size of these channels, preferably to a subwavelength-scale diameter [11,12], as well as selective excitation of guided modes supported by such waveguide wires.

2. Random-hole microstructure fibers

Random-hole MS fibers were fabricated by drawing a preform consisting of fused silica capillaries with different inner diameters. A cross-section view of the fiber is presented in Fig. 1. The microstructured part of the fiber includes two sections with radically different sizes of air holes (Fig. 1(a)). The size of air holes in the outer section is typically about 20 µm. This outer microstructured part serves as a cladding, confining light to the inner microstructured part of the fiber (Fig. 1(a)), where the sizes of air holes vary from 0.3 up to 2 µm. Instead of a single central core, this inner microstructure part of the fiber guides light through an array of fused silica channels with diameters typically ranging from 0.6 up to 1.5 µm. Each of these channels can be viewed as a fiber core surrounded by a random holey cladding, providing waveguiding due to the total internal reflection. MS fibers of this type have been analyzed earlier, both experimentally and theoretically, by Monro et al. [14].

As shown by earlier theoretical work [11,12], air-cladding submicron-diameter waveguiding wires provide optimal conditions for efficient nonlinear-optical transformation of laser pulses within the visible range of wavelengths. An MS fiber integrating an array of waveguide channels with varying diameters, as shown in Fig. 1, is therefore ideally suited as a broadly tunable multiplex frequency converter for low-power femtosecond laser pulses. Large-size air holes in this MS fiber confine guided modes to the waveguiding channels, isolating these channels from each other and reducing the cross-talk between the neighboring waveguides. The dual-scale architecture of the microstructure part of the fiber is, on the other hand, advantageous for the creation of MS-fiber sensors, as earlier demonstrated by Myaing et al. [15]. Waveguide channels in our MS fibers, on the other hand, have substantially higher losses than PCFs with a regular structure or tapered fibers. The magnitude of losses was estimated as 4 dB/m for channel 1 and 10 dB/m for channel 4 in Fig. 1(b).

We identify two typical geometries of waveguide channels in the fabricated MS fiber. Waveguide channels of the first type are bounded by a triad of air holes and have a triangular shape (channels 2, 3 in Fig. 1(b)). Waveguides of the second type are bounded by four air holes, defining a rectangular shape of the channel (channels 1, 4 in Fig. 1(b)). Figure 2 presents dispersion properties (Fig. 2(a)) and field intensity profiles (Figs. 2(b), 2(c)) for the guided modes supported by these two types of waveguide channels simulated by the finite-element technique (FET). Our numerical simulations confirm that the waveguide channels of both types support well-localized modes of electromagnetic field, confined to the high-index
material, with only about 10% of radiation power guided in the evanescent field in the air holes. Calculations of the group-velocity dispersion (GVD) for these guided modes as a function of the radiation wavelength (Fig. 2(a)) illustrate the possibility to switch the zero-GVD point by coupling the pump field into waveguiding channels with different diameters, suggesting a convenient way to spectrally tune the frequency conversion of laser pulses through soliton–dispersive waves [16] and four-wave mixing [17-19] nonlinear transformation mechanisms. To check the results of FET calculations, the GVD was measured for different waveguide channels in the MS fiber using the pulse-delay technique developed by Ouzounov et al. [20]. A Ti: sapphire laser generating 70-fs pulses of radiation tunable from 750 to 900 nm and a two-photon detector were employed for these measurements. Typical experimental data are presented by squares in Fig. 2(a). FET simulations, as can be seen from this plot, provide a reasonable fit for the GVD of waveguide channels.

3. Laser setup

In experiments, we used a self-starting, self-mode-locked Ti: sapphire oscillator, running at a central wavelength of 820 nm at a pulse repetition rate of 80 MHz. A semiconductor saturable absorber mirror (SESAM) was incorporated into the laser cavity to ensure robust self-starting. The maximum average output power of laser radiation was 800 mW. A Faraday isolator was placed behind the Ti: sapphire oscillator to prevent retroreflected radiation from disturbing the operation of the laser oscillator. The laser pulses transmitted through extracavity optical components were recompressed to a pulse duration of 30 fs by a double-pass prism compressor, which compensated for pulse stretching caused by the Faraday isolator.

The recompressed pulses were coupled into the MS fiber with a 40x objective lens (0.65 N.A.) or a 20x objective lens (0.40 N.A.), providing the coupling efficiencies of 15 and 30%, respectively. Radiation coming out of the fiber was collimated with a micro-objective and was split into two beams. One of these beams was delivered to a spectrograph, while the other one was used to visualize the transverse intensity distribution in the emission coming out of the microstructure fiber by imaging the output mode of the fiber onto a CCD camera. Spectral measurements were performed with an optical spectrum analyzer (Ando, AQ6315A).

![Fig. 2. (a) Group-velocity dispersion as a function of the wavelength for channels 1 - 5 (curves 1 - 5, respectively) in the microstructure fiber shown in Fig. 1. Squares present experimental data. (b, c) Transverse intensity profiles for the fundamental mode of (b) the rectangular waveguide channel bounded by four air holes and (c) the triangular waveguide channel bounded by three air holes.](image-url)
4. Results and discussion

For small-diameter waveguiding channels (channels 1 - 3 in Fig. 1(b)), the wavelength of Ti:sapphire laser radiation, used as a pump in our experiments, falls within the range of anomalous dispersion (curves 1 - 3 in Fig. 2(a)). The propagation of the pump pulse through the waveguide is accompanied by soliton formation under these conditions. The spectra of radiation transmitted through the waveguide channels in the MS fiber (Figs. 3) reveal distinct solitonic features. In particular, self-frequency-shifted solitons [21] give rise to the spectral peaks red-shifted with respect to the pump wavelength (Figs. 3(a), 3(b)), while non-solitonic, dispersive-wave emission shows up as an intense peak in the anti-Stokes part of the spectrum. With the energy of input femtosecond pulses lying in the subnanojoule range, this anti-Stokes-shifted emission carries up to 20% of radiation energy at the output of the fiber, indicating a high efficiency of frequency conversion. Rectangular (Fig. 4(a)) and triangular (Figs. 4(b), 4(c)) output beam patterns of anti-Stokes emission are ideally fitted by the field intensity profiles calculated for the waveguide channel bounded by four (Fig. 2(b)) and three (Fig. 2(c)) air holes, respectively. Experimental measurements confirm that the field is well localized in these guided modes, being confined to fused silica waveguiding channels. With 200-mW pump pulses coupled into submicron channels of a 3-cm-long MS fiber with a coupling efficiency of about 30%, we observed the generation of supercontinuum, with the flat plateau in the spectrum of output emission stretching from 450 to 1060 nm (Fig. 3(c)).

Interestingly and quite importantly, approximately 10% of the energy of radiation emitted into the spectrally isolated 420-nm anti-Stokes signal (Figs. 3(a), 3(b)) is guided in the evanescent field displaced to the air holes (Fig. 4(a)), which agrees well with our finite-element simulations. This evanescent part of the anti-Stokes field can be conveniently used for sensing applications. Spectrally isolated anti-Stokes signals with different frequencies, generated by femtosecond pump pulses of the same wavelength coupled into different waveguide channels, then allow a multiplex, panoramic spectroscopic analysis of gas- or liquid-phase species filling the array of holes in the fiber. Supercontinuum emission, on the other hand, can be employed for a broadband spectral analysis of such species.

Waveguiding channels with larger diameters (channels 4 - 6 in Fig. 1(b)) are characterized by a lower waveguide dispersion, with the zero-GVD point shifted toward longer wavelengths. The pump wavelength lies in the normal dispersion regime for the fundamental modes of such waveguides (curve 5 in Fig. 2). Regime of anomalous dispersion is achieved for higher order modes in these waveguides, with Ti:sapphire laser pulses tending to produce solitons emitting dispersive waves with transverse intensity profiles typical of high-order guided modes. Figures 4(d)-4(f) display the basic colors of palette (red, green, and blue) produced by 20-mW 30-fs Ti:sapphire laser pulses in high-order modes of waveguide
channels 4 - 6 (Fig. 1(b)) of a random-hole MS fiber with a length of only 3 cm. Since the spectra at the output of the fiber display peaks close to 400 nm, special precautions have been taken to avoid artifacts related to second-order reflection of the pump from gratings in the spectrum analyzer. In particular, the pump beam produced no signal around 400 nm in our detection system in the absence of an MS fiber.

![Output beam patterns of anti-Stokes-shifted emission from channels 1 - 6 in Fig. 1(b) (a -- f) of the random microstructure fiber.](image)

**5. Conclusion**

We have shown that an array of fused silica waveguiding channels with randomly distributed transverse sizes in disordered MS fibers can provide highly efficient broadly tunable frequency conversion of low-energy ultrashort laser pulses. Dispersion can be switched in such waveguide arrays by coupling the pump field into waveguiding wires with different diameters. Dispersive-wave emission of solitons in an array of such waveguides with diameters ranging from 0.6 up to 1.5 µm can frequency-convert unamplified Ti: sapphire laser pulses with an initial duration of 30 fs to any wavelength within a broad spectral range from 400 up to 700 nm, suggesting the ways of creation of random microstructure fiber multiplex frequency converters and sensors.

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