# Mode-controlled colors from microstructure fibers

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**Abstract:** We experimentally demonstrate mode-controlled spectral transformation of femtosecond laser pulses in microstructure fibers. Depending on the waveguide mode excited in the fiber, 30-fs Ti: sapphire laser pulses can either generate a broadband emission or produce isolated spectral components in the spectrum of output radiation. This method is used to tune the frequencies dominating the output spectra, controlled by phase matching for four-wave mixing processes.



**OCIS codes:** (190.4370) Nonlinear optics, fibers; (190.7110) Ultrafast nonlinear optics

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## 1. Introduction

Unique properties of microstructure (MS) fibers [1, 2] allow high efficiencies of nonlinear-optical interactions to be achieved even for low-power ultrashort laser pulses [3]. Dispersion of such fibers can be broadly tuned by varying their core--cladding geometry [4]. A high refractive index step between the core and the cladding, attainable with such fibers, provides a strong confinement of electromagnetic radiation in the fiber core [5, 6], enhancing nonlinear processes and leading to efficient generation of radiation with a very broad spectrum (supercontinuum) [7 - 9]. Microstructure fibers, as shown by experiments on third-harmonic generation [10, 11] and four-wave mixing [12], offer new solutions to the phase-matching problem, allowing the frequency of low-energy femtosecond pulses to be efficiently converted to isolated wavelength-tunable spectral components [13, 14]. Microstructure-fiber frequency converters substantially enhance the capabilities of low-energy femtosecond lasers in photochemistry [15] and nonlinear spectroscopy [16].

In this work, we experimentally demonstrate mode-controlled spectral transformation of femtosecond laser pulses in microstructure fibers. We will show that the regime of supercontinuum generation in a microstructure fiber can be switched to the regime where isolated spectral components are generated by coupling femtosecond Ti: sapphire laser pump pulses into different guided modes of a microstructure fiber. This method of control can be also used to tune the frequencies dominating the spectrum of radiation at the output of a microstructure fiber.

## 2. Analysis of modes guided in microstructure fibers

Our experiments were performed with a family of fused silica microstructure fibers where the cladding consisting of several cycles of air holes surrounds the central fiber core with a diameter of a few micrometers (Fig. 1). Microstructure fibers were fabricated of fused silica

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using the technology described in detail elsewhere [16]. Our experiments were performed with microstructure fibers having two cycles of air holes around the central fiber core with a diameter of about 4.5 μm. The air-filling fraction of the microstructure part of the cladding in the created fibers, as can be seen from Fig. 1, is very high, providing a high refractive index step between the core and the cladding in the fiber and strongly confining the light field to the fiber core.

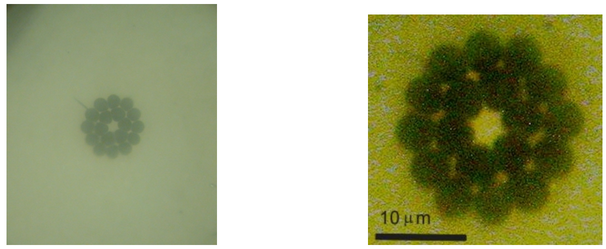


Fig. 1. Cross-section images of a microstructure fiber: (a) the general view of the microstructure part of the fiber in the outer shell, (b) the central, microstructure part of the fiber.

Our method of numerical analysis of guided modes in microstructure fibers was based on a modification of the approach proposed by Monro *et al*. [17, 18]. We numerically solved [19] the Maxwell equations for the transverse components of the electric field in the cross section of a microstructure fiber. The transverse distribution of the electric field in the cross section of the fiber was represented as an expansion in orthonormalized Hermite--Gauss polynomials. The two-dimensional profile of the refractive index squared in the cross section of the fiber, $n(x, y)$, was also represented as an expansion in Hermite--Gauss polynomials and a set of orthogonal periodic functions. Substituting these functional series into the wave equations reduces the initial vectorial problem to an eigenfunction and eigenvalue problem for the relevant matrix equation. Solving this problem, we can find the propagation constants and spatial field distributions in waveguide modes.

The number of modes supported by the fiber core increases with the growth in the ratio of the fiber core diameter to the radiation wavelength and with the increase in the refractive index step between the core and the cladding. In view of the large core diameter and a high refractive index difference between the fused silica core and the microstructure cladding, MS fibers employed in our experiments are multimode waveguides. Figures 2 and 3 illustrate dispersion properties and present typical field intensity profiles for the fundamental and higher order guided modes in MS fibers of the considered type. The fundamental mode is a doublet of degenerate modes with electric-field intensity reaching its maximum at the center of the fiber core and monotonically decreasing off the center of the fiber (Fig. 2(a)). Higher order modes form degenerate multiplets (Figs. 2(b), 2(c)), with their superposition supporting the full symmetry of the fiber (Fig. 2(d)), identified as $C_{v6}$ in our case. This result agrees well with the analysis of MS-fiber modes based on general symmetry arguments [20]. The fundamental mode of the considered MS fiber (Fig. 2(a)) has the maximum propagation constant $\beta$ (Fig. 3), and its group-velocity dispersion (GVD) passes through zero around a wavelength of 990 nm (the inset in Fig. 4).The zero-GVD wavelengths for higher order modes are shifted to the blue with respect to the zero-GVD point of the fundamental mode (the inset in Fig. 4).

### 3. Experimental results and discussion

Dispersion of guided modes controls phase matching for wave-mixing processes, thus determining the efficiency of energy exchange between different frequency components of broadband emission generated by ultrashort pulses in MS fibers. Dispersion analysis shows that the fundamental mode in an MS fiber with a core diameter of 4.5 μm allows no phase


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matching for the parametric four-wave mixing process $2\omega_p = \omega_s + \omega_a$ ($\omega_p$ is frequency of pump radiation and $\omega_s$ and $\omega_a$ are the frequencies of the Stokes and anti-Stokes signals, respectively) with the pump wavelength $\lambda_p$ around 800 nm. The doublet of higher order modes with intensity profiles shown in Figs. 2b-2d (see also the inset to Fig. 3) and dispersion represented by the red curve in Fig. 3, on the other hand, allows phase-matched four-wave mixing $2\omega_p = \omega_s + \omega_a$ with Ti: sapphire laser pulses used as a pump (Fig. 4). The wavelength $\lambda_0$ of zero group-velocity dispersion for these modes lies close to the radiation wavelength of a Ti: sapphire laser (the inset in Fig. 4), which permits dispersion pulse spreading to be reduced and phase matching to be achieved for parametric four-wave mixing [14, 21]. The mismatch of propagation constants $\delta\beta$ for the studied wave-mixing process as a function of the wavelength is shown in Fig. 4. For a pump wavelength of 800 nm, the phase-matching condition $\delta\beta = 0$ is satisfied, as can be seen from Fig. 4, with an anti-Stokes wavelength of approximately 570 nm. The phase matching is shifted to the anti-Stokes wavelength of about 560 nm if 795-nm radiation is used as a pump. Efficient generation of anti-Stokes radiation within this wavelength range can thus be expected in the considered mode of the MS fiber.

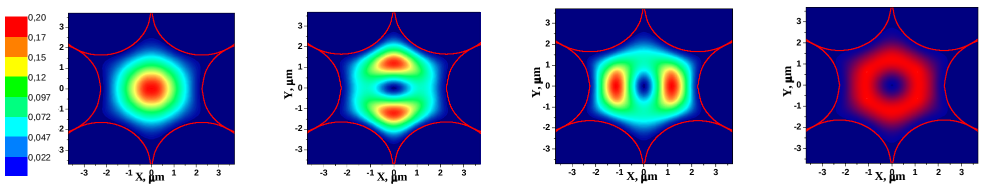


Fig. 2. Intensity distributions in (a) the fundamental and (b, c) a degenerate doublet of higher order modes of the microstructure fiber shown in Fig. 1. Superposition of the degenerate doublet of modes (b, c) yields an $HE_{21}$-mode-type intensity distribution (d). The fiber core diameter is 4.5 µm. The radiation wavelength is 570 nm.

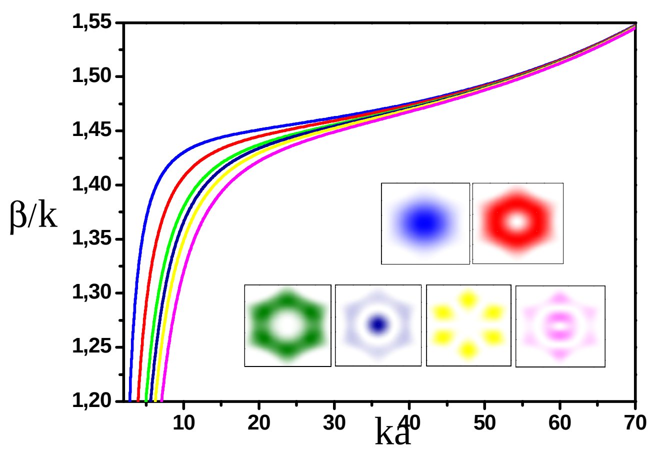


Fig. 3. Propagation constant $\beta$ normalized to the wave number $k = \omega/c$ ($\omega$ is the frequency and $c$ is the speed of light) as a function of dimensionless frequency $ka$ ($a$ is the diameter of holes in the fiber cladding) for the fundamental (blue curve) and higher order (red, green, navy, yellow, and pink) guided modes of the microstructure fiber shown in Fig. 1. The insets show intensity profiles for the fundamental (blue) and higher order (red, green, navy, yellow, and pink) guided modes in the microstructure fiber. The fiber core diameter is 4.5 µm.

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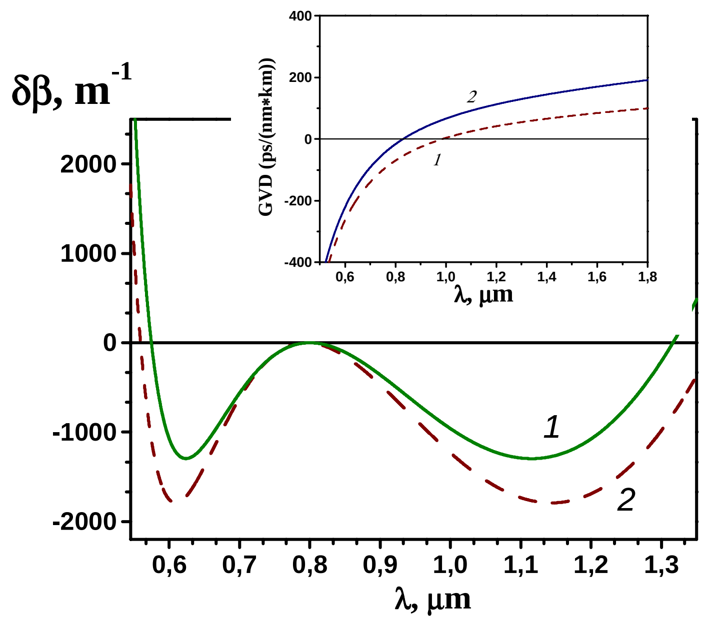


Fig. 4. Mismatch of propagation constants $\delta\beta$ of higher order waveguide modes involved in the FWM process $2\omega_p = \omega_s + \omega_a$ in a fused silica MS fiber with a core diameter of 4.5 μm. The pump wavelength is 800 nm. The inset shows the group-velocity dispersion (GVD) calculated for the fundamental (dashed line *1*) and higher order (solid line *2*) guided mode of the microstructure fiber.

Our experiments were performed with regeneratively amplified Ti: sapphire laser pulses with an initial pulse duration of about 30 fs. A standard micro-objective was used to couple these laser pulses into the microstructure fiber, placed on a three-dimensional translation stage. Spectral measurements were carried out with an Acton spectrometer and a CCD camera. Depending on the initial conditions on the input end of the fiber, femtosecond pulses of Ti: sapphire laser radiation generated either a broadband emission (Fig. 5(a)) or new isolated spectral components (Fig. 5(b)). This mode control over the regime of nonlinear-optical spectral transformation of femtosecond pulses is due to the difference in dispersion properties of MS-fiber modes.

The pump wavelength $\lambda_p$ = 800 nm falls within the regime of normal dispersion for the fundamental mode of the MS fiber (see the inset in Fig. 4), resulting in the generation of moderately broadband emission (Fig. 5(a)), observed as an orange spot at the output of the fiber (the inset in Fig. 5(a)). For the doublet of modes with the $HE_{21}$-type superposition intensity profile (Fig. 2(d)), the pump wavelength $\lambda_p$ = 800 nm lies in the anomalous-dispersion range close to the zero-GVD point $\lambda_0$ (see the inset in Fig. 4). This situation is optimal for phase-matched four-wave mixing [14, 22]. Efficient generation of a spectrally isolated anti-Stokes frequency component centered at $\lambda_a$ = 560 nm is illustrated by the output spectra presented by the solid line in Fig. 5(b). The beam pattern at the output end of the fiber (the inset to Fig. 5(b)) clearly indicates that this anti-Stokes emission is predominantly generated in higher order guided modes. Experimental results thus agree very well with our expectations based on dispersion analysis of MS fibers, which shows that four-wave mixing $2\omega_p = \omega_s + \omega_a$ involving higher order guided modes of an MS fiber is phase-matched with $\lambda_p$ = 800 nm and $\lambda_a$ = 570 nm. Increasing the energy of the input pump pulse, we observed broadening of the output spectrum (the dashed line in Fig. 5(b)). The anti-Stokes signal eventually merged together with the long-wavelength part of the spectrum, giving rise to supercontinuum emission in accordance with the physical scenario of nonlinear pulse propagation in microstructure fibers in the anomalous GVD regime [21 - 24].

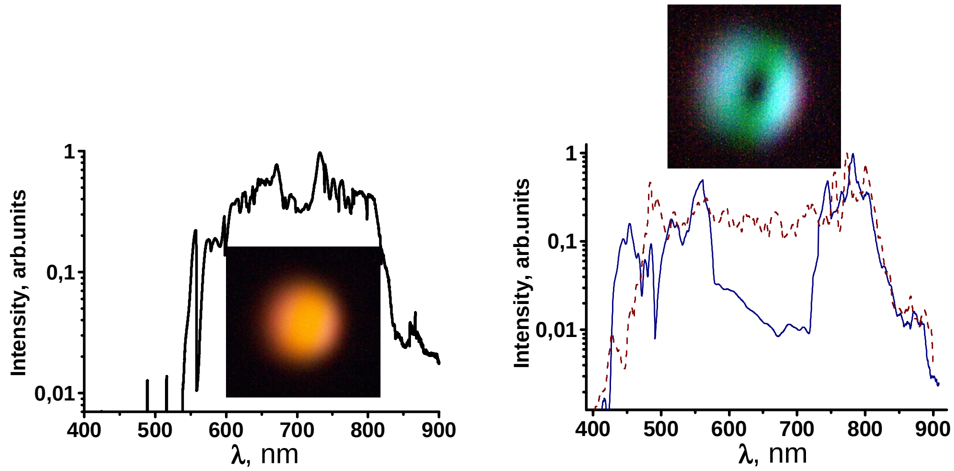


Fig. 5. The spectra of Ti: sapphire laser pulse with an initial pulse duration of 30 fs transmitted through a 6-cm section of the microstructure fiber in (a) the fundamental and (b, c) higher order waveguide modes. The input pulse energy is (a) 100 nJ and (b) 100 nJ (solid line) and 200 nJ (dashed line). The insets show the images of the output end of the fiber.

## 4. Conclusion

Our experiments demonstrate the possibility to switch between the regimes of broadband radiation emission and generation of isolated spectral components in microstructure fibers by coupling pump radiation into different waveguide modes, resulting in a quite fascinating variation of colors of higher order modes produced at the output of the microstructure fiber. This method also allows the frequencies dominating the spectrum of output radiation to be controlled in a simple and practical way.

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