Broadband supercontinuum generation in tapered multimode graded-index optical fibers

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Abstract: We experimentally demonstrate for the first time uniform and broadband supercontinuum generation in long tapered multimode fibers. This is achieved through an accelerated geometric parametric instability that forces the sidebands towards higher/lower frequencies.

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Supercontinuum generation (SC) is these days finding extensive applications in biomedical imaging, optical metrology, spectroscopy, and sensing, to mention a few [1]. In this regard, single-mode photonic crystal fibers with pre-engineered dispersion characteristics are currently commercially used in implementing spatially coherent ultra-bright SC sources, spanning the wavelength range from ultraviolet to the mid-infrared [2]. Given that most of the SC sources have so far relied almost exclusively on single mode or few mode fiber technologies, it will not be long before limits are reached in terms of output power capabilities. To this end, a possible avenue to overcome these hurdles could be to use large-area multimode fibers (MMFs). These fibers are by nature complex structures: they can support thousands of modes that can in turn interact among themselves in a variety of ways. Quite recently, the nonlinear "virtues" of nonlinear MMFs have been reconsidered in both the normal and anomalous dispersion regimes. Supercontinuum generation has also been successfully demonstrated in graded index MMFs by launching ultra-short pulses in the anomalous dispersion region (1550 nm) [3]. In addition, efficient supercontinuum generation from the visible to mid-infrared (when pumped in the normal dispersion, 1064 nm) was reported in low DGD parabolic MMFs [4]. The main mechanism behind this generation of supercontinuum in the visible regime is a geometric parametric instability that occurs in fibers with parabolic index profile through periodic contraction/expansion of light along propagation [5]. This geometric parametric instability process couples light into a series of sidebands situated symmetrically around the pump. The beating frequency of the field intensity along propagation which is proportional to the locations of the sidebands, is determined by the fiber numerical aperture and core radius. The angular frequency of the generated *m*th sideband can be obtained from $\omega_{SB_m} \simeq \omega_p \pm \sqrt{m}\,\omega_G$, where $\omega_G^2 = 2\delta/|k_0''|$. Here $\delta = a^{-1}\sqrt{2\Delta}$ represents the spacing between the eigenvalues, $|k_0''|$is the fiber dispersion at the pump wavelength, and $\Delta = (n_{core} - n_{clad})/n_{core}$. In our study, the pump wavelength is taken to be 1064 nm ($|k_0''| = 1.6 \times 10^{-26} m^{-1} s^2$) while the index difference is $\Delta = 0.01$. In what follows, we show that the SC spectrum can be effectively homogenized by "accelerating" the nonlinear processes in a tapered multimode fiber. This in turn forces the sidebands (ω_{SB_m}) to continuously drift away from the pump frequency through this geometric parametric instability. To do so, we vary the core radius as a function of distance.

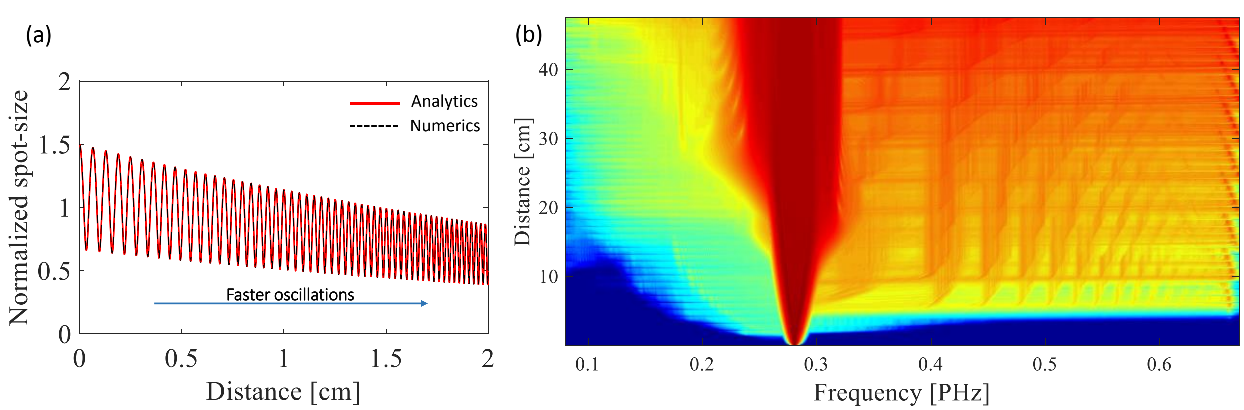

Fig.1 (a) Accelerated beating dynamics in a tapered multimode parabolic optical fiber. (b) simulated SC generation in a tapered parabolic fiber, when excited at 1064 nm. A continuous drift of the sidebands towards higher/lower frequencies is clearly observed.

Tapering technology offers unique possibilities in terms of altering the modal structure and composition along the fiber, something that can be exploited to enhance nonlinear processes. In this work, the longitudinal fiber transition is judiciously designed in order to control both spatial and temporal interactions – potentially leading to highly customized multimode SC light sources. Based on this idea, one expects that the generated sidebands will gradually experience stronger blue-shifting towards the visible and respectively red-shifting in the MIR, as the core diameter decreases. This, in turn, will encourage the GPI response to eventually cover a wider spectral region through this acceleration of the spatiotemporal compression of light. Interestingly, the beating dynamics in core-decreasing parabolic fiber arrangements can be obtained analytically by exactly solving the resulting Ermakov equation. From here, the z-dependent field spot-size in an exponentially tapered parabolic fiber can be obtained from the following analytical result:

$$w^2 = \left[AJ_0\left(\frac{e^{\beta\xi}}{\beta}\right) + BY_0\left(\frac{e^{\beta\xi}}{\beta}\right)\right]^2 \left(1 + \frac{1}{C_Q^4\beta^2}\left(\tan\left(\frac{e^{\beta\xi}}{\beta} - \phi\right) - \tan\left(\frac{1}{\beta} - \phi\right)\right)^2\right)$$

where β is the tapering parameter, ξ is a normalized propagation distance, while C_Q and A and B are constants, depending on initial conditions. Figure 1(a) depicts the variation of the spot size during propagation in such a tapered fiber where an acceleration in the beating oscillations is apparent.

To numerically model the supercontinuum generation in a such a tapered multimode fiber, we have used a gUPPE approach [5]. This unidirectional pulse propagator (UPPE) allows one to model supercontinuum generation in highly multimode MMFs in a global manner and takes into account all the linear and nonlinear processes. The silica fiber under investigation is assumed to have a core radius that decreases exponentially as a function of distance from 40 µm to 10 µm over a distance of 50 cm ($NA = 0.21$). This MMF is excited at 1064 nm where the dispersion is normal and supporting ~ 900 modes at the origin. Figure 1(b) depicts the results of this simulation up to 50 cm. Our simulations show that all the generated sidebands experience an accelerated drift toward higher/lower frequencies as the fiber is gradually narrowing down.

To verify this behavior, a series of experiments were carried out using a Q-switched microchip laser at 1064 nm (400 ps, 95 µJ and 500 Hz). The multimode fiber taper is ~ 15 m long and has the same numerical aperture used in our numerical studies. The core radius is decreased from 50 µm to 10 µm over a distance of 15 m. Figures 2 shows, the output spectra resulting from this excitation. In agreement with our numerical results, we observe a flat spectrum, extending from 400 nm to 2400 nm. These intriguing dynamics are the direct byproduct of an accelerated geometric parametric instability. Our results may pave the way towards new classes of SC multimode fiber sources.

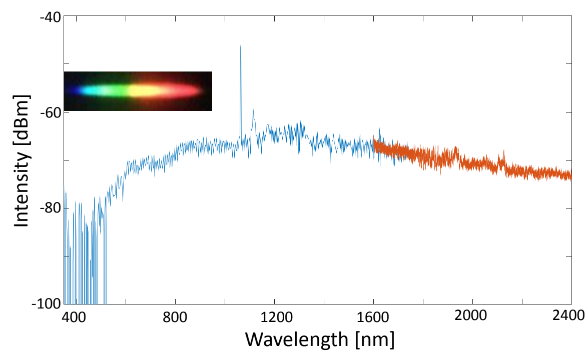

Fig. 2 Experimentally observed SC spectrum in a tapered parabolic multimode fiber with an NA=0.21. The data was collected using two different spectrometers. In all cases, the spectrum is homogenized as a result of tapering. The visible part of the spectrum is also depicted in the inset.

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