Modulational Instability in Normally Dispersive Tapered Multimode Fibers

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Abstract: We show that modulational instability can occur in normally dispersive adiabatically tapered parabolic multimode fibers. Experimental results corroborate this intriguing phenomenon at 1.064 μm, indicating that the sideband gain is dictated by the tapering rate.

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Modulational instability (MI) is a ubiquitous process that is known to occur in many and diverse physical settings, ranging from fluid dynamics and plasmas to nonlinear optical fibers and Bose-Einstein condensates. This phenomenon-a precursor to soliton formation-is innately related to the very stability properties of the underlying nonlinear Schrödinger equation governing these phenomena. In general, this effect is only possible in the anomalous dispersive region while it is prohibited in the normal regime. Perhaps the only exception to this rule is when two or more waves interact in a nonlinear environment in which case cross-phase modulation and four-wave mixing effects now play a decisive role [1]. Thus far, MI has been observed in normally dispersive birefringent fibers involving two polarizations or in systems with axially varying linear and nonlinear properties [2-4]. Importantly, MI is among the critical processes participating in the generation of broadband supercontinuum in single-mode fibers, that is nowadays finding applications in a wide range of technical fields. Quite recently, efficient supercontinuum generation stretching from the visible to mid-infrared (when pumped in the normal dispersion, 1064 nm) has been reported for the first time in low DGD parabolic multimode fibers (MMFs) [5]. These latter results suggest that MMFs can provide a versatile platform where broadband supercontinuum can be produced with spectral densities that are orders of magnitude higher that those obtained in photonic crystal single-mode fibers. In view of these developments, of interest will be to investigate how nonlinear effects unfold in tapered MMFs, a topic that still remains relatively unexplored.

In this work, we show that surprisingly MI can appear in the normal dispersive regime of a tapered multimode parabolic optical fiber. This prospect is predicted via analytical results and supported by numerical simulations. Experiments carried out at 1064 nm confirm the rise of sidebands, as predicted by analytical and numerical studies. While in tapered single-mode arrangements MI is entirely absent, in multimode configurations the fundamental mode experiences a variant of this instability that is now dictated by the tapering rate, irrespective of the sign of dispersion.

Figures 1(a) and (b) depict the temporal and spectral evolution of a $\sim 130\ fs$ pulse propagating in a parabolic MMF with a $NA = 0.21$, as obtained from numerical simulations. The operating wavelength is $1064\ nm$ and the fiber is tapered within 1 m, from a core diameter of 120 to 16 μm. The peak power used is $700\ W$ and initially the fundamental mode of the fiber is excited. Our study clearly shows that because of tapering, new sideband frequencies are produced and as a result the pulse disintegrates in time, marking the onset of MI. Note that in the absence of any tapering, this same MMF prohibits MI when excited at 1064 nm (Fig. 1(c,d)).

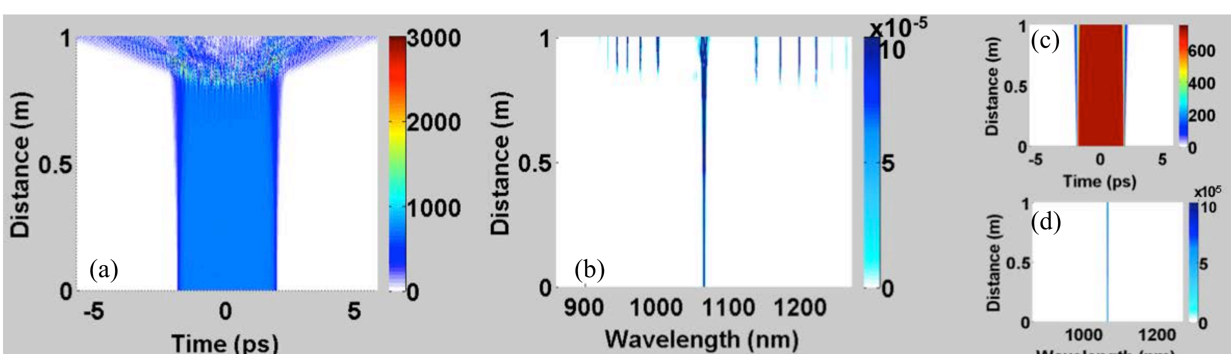

Fig. 1. (a) Temporal and (b) spectral evolution of a 130 fs pulse in a tapered parabolic MMF. The peak power is 700 W and the pump wavelength is 1064 nm. The presence of MI is evident. (c)-(d) Absence of MI in a non-tapered MMF, both in time and in spectrum.

To theoretically understand these results we perform linear stability analysis on the underlying evolution equation in this tapered MMF by assuming a perturbation of the form $\epsilon(z,t) = a(z)\exp(i\Omega t) + b(z)\exp(-i\Omega t)$ where $a(z), b(z)$, denote sideband amplitudes. From here, one can analytically show that

$$a(z) = e^{(\kappa/2)z}\left[C_1 J_\nu\left(i\frac{2}{\kappa}\sqrt{2\alpha\Omega^2\gamma u_0^2}e^{(\kappa/2)z}\right) + C_2 Y_\nu\left(i\frac{2}{\kappa}\sqrt{2\alpha\Omega^2\gamma u_0^2}e^{(\kappa/2)z}\right)\right], \qquad (1)$$

where J_ν and Y_ν stand for Bessel functions of general order ν. Here, $\nu = (1/\kappa)\sqrt{\kappa^2 - 4(\alpha^2\Omega^4 - i\kappa\alpha\Omega^2)}$, $\alpha = -\beta''/2$, κ is the tapering parameter, and Ω represents the generated sideband frequencies. Because of the nature of this solution $a(z)$, the perturbation is exponentially increasing regardless of the sign of dispersion (Fig. 2 (a)). In other words, MI is now possible in the normal dispersion. The temporal and spectral profiles at the output of this tapered fiber are shown in Figs. 2(b) and (c), respectively, as obtained from numerical simulations. These results are in agreement with the predictions of Eq. (1). The temporal pulse breaks apart because of MI and spectral MI sidebands consequently appear at 976, 1001, 1138, and 1171 nm.

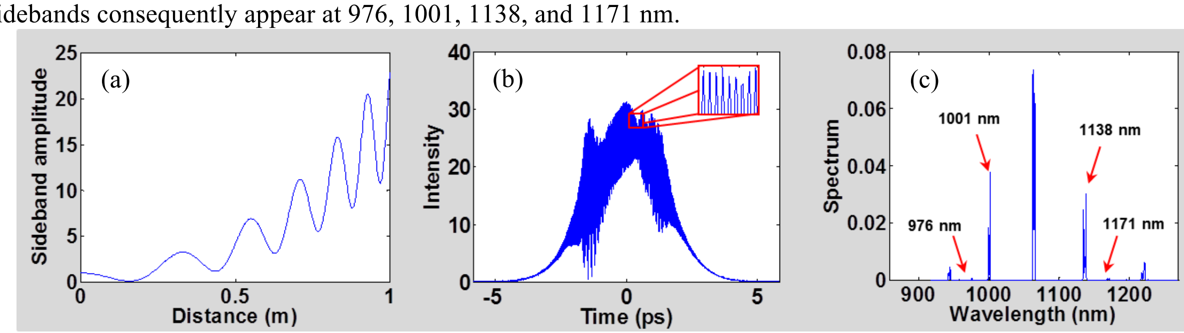

Fig. 2. (a) Perturbation growth as a function of propagation distance in the normal dispersion regime of a tapered MMF. (b) Temporal profile, and (c) resulting spectrum after 1 m propagation distance. The parameters used are $P_0 = 700\,W$, $T_0 = 0.13\,ps$, $\lambda_0 = 1064\,nm$, $\beta'' = 1.6427\times 10^{-26}s^2/m$.

To verify our predictions, an experiment was carried out using a Q-switched microchip laser at $1064\,nm$ ($400\,ps$, $95\,\mu J$ and $500\,Hz$). The multimode fiber taper is $\sim 1\,m$ long and has a numerical aperture of 0.21. The core radius decreased from 60 to 8 μm over $1\,m$. While in a standard fiber (Fig.3(a)) no MI occurs, in its tapered counterpart new frequencies appear (Fig. 3(b)), in close agreement with our theoretical and numerical predictions.

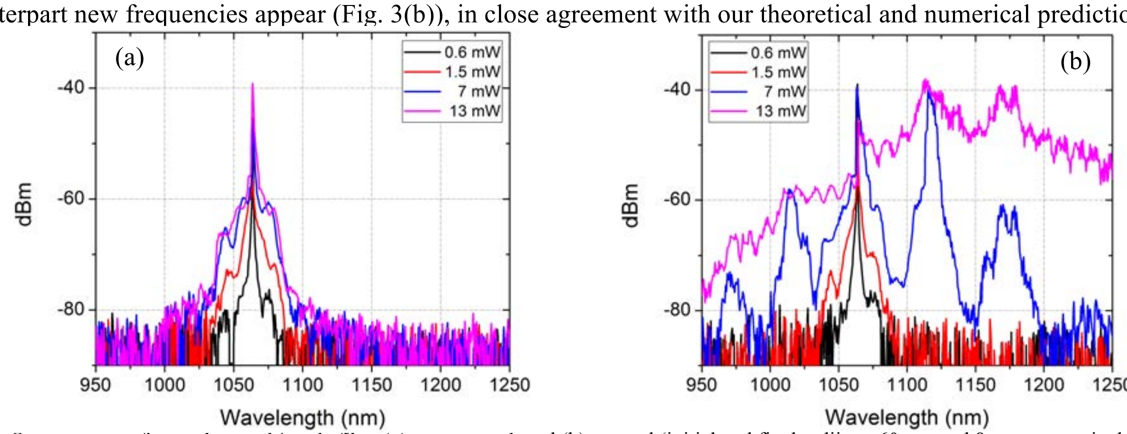

Fig. 3. Output spectra from a 1 m multimode fiber (a) non-tapered, and (b) tapered (initial and final radii are 60 µm and 8 µm, respectively), used in the normal dispersive regime ($\lambda_0 = 1064\,nm$). At an average power of 7 mW, sidebands are observed at 970 nm, 1014 nm, 1116 nm, and 1173 nm, in agreement with our numerical and analytical results.

In conclusion, we have demonstrated that MI is possible in normally dispersive tapered MMFs. This effect has no counterpart in either single mode arrangements or non-tapered MMF systems.

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