Analysis of Parametric Instabilities in Parabolic Multimode Fibers under High Intensity Conditions

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Abstract: We systematically study geometric parametric instabilities in parabolic multimode fibers. We show, both analytically and experimentally, that global dispersion processes and self-focusing effects can substantially affect the spectral positions and widths of the generated sidebands.

OCIS codes: (190.4370) Nonlinear optics, fibers; (190.4410) Nonlinear optics, parametric processes

Parametric instabilities are ubiquitous phenomena that are known to take place in systems having one or more parameters that are periodically varying in time or space. Quite recently, a geometric version of this effect was successfully observed in nonlinear parabolic multimode optical fibers (MMFs) [1,2]. This geometric parametric instability (GPI) results from periodic beam revivals that in turn cause intensity compressions/expansions during propagation. What enables this mechanism in this type of graded-index fibers is the equidistant separation of the propagation constants-an attribute that also significantly suppresses the differential group delays between modes in these systems. As a result, a continuous wave or a broad pulse can become unstable, thus leading to the generation and amplification of spectral sidebands. Interestingly, the GPI process can take place in both dispersive regions, irrespective of whether is normal or anomalous. Even though the location of the GPI induced sidebands can be approximately predicted via perturbative schemes [3-5], a rigorous analysis of these effects is still lacking-especially in regimes where self-focusing revivals in multimode fibers could be an issue.

In this work, we provide a rigorous analysis that includes dispersion to all orders while at the same time is capable of describing spatial self-focusing oscillations along the fiber axis. Note, that under these conditions, a perturbative treatment is no longer valid. Analytical results based on an exact Floquet theory and supported by numerical simulations indicate that as the input power is increased, the generated GPI sidebands start to move closer to the pump wavelength and experience higher amplification rates. In addition, the dependence of the GPI stability diagram on the input peak power is also investigated both theoretically and experimentally.

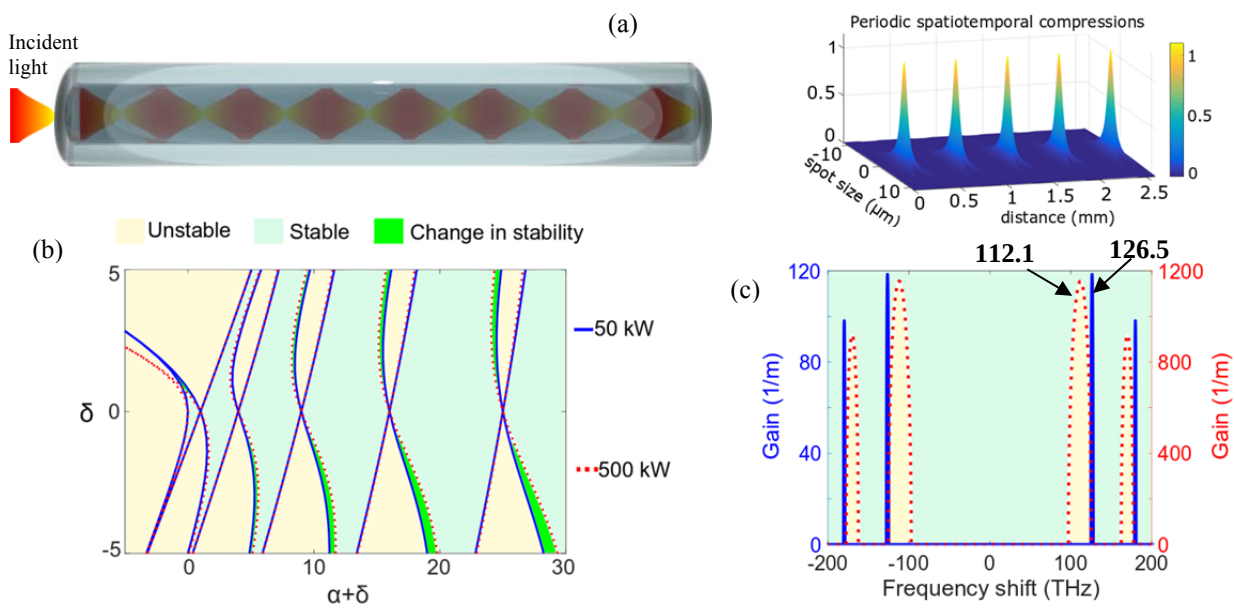

Fig. 1. (a) Periodic spatiotemporal compressions in a parabolic MMF. (b) Change in the stability diagram associated with the Hill's equation as the input power in increased from $50\,kW$ to $500\,kW$, and (c) the corresponding GPI gain spectrum. The parameters used here are $\lambda_0 = 1064\,nm$, $a = 25\,\mu m$, $w_i = 15\,\mu m$. The blue curves correspond to a peak power of $50\,kW$ while the red to $500\,kW$.

To demonstrate these effects we consider an input beam of $w_i = 15\ \mu m$ diameter propagating inside a parabolic MMF having a core radius of $25\ \mu m$. The operating wavelength is $1064\ nm$ and the peak power is taken to be $50\ kW$. From the fiber parameters we find that the period of the spatial oscillations in this MMF is $0.55\ mm$ (Fig. 1(a)). As the input power is increased to $500\ kW$, the transition curves separating the stable and unstable regions are altered in such a way that the unstable regions become wider (Fig. 1(b)). As a result, frequencies closer to the pump now start to experience considerably higher gains and their spectrum location and width is substantially affected as the input peak power increases (Fig. 1(c)).

To theoretically understand these results, let us consider the evolution of the optical field envelope in a parabolic MMF, which is known to obey a (3+1)D generalized nonlinear Schrödinger equation (GNLSE). Higher-order dispersion terms are also accounted in the GNLSE. To estimate how the spatiotemporal oscillations lead to specific GPI bands in the frequency domain we assume a perturbation of the form $\epsilon(z,t) = c_1(z)\exp(i\Omega t) + c_2(z)\exp(-i\Omega t)$, where $c_1(z)$, $c_2(z)$ denote sideband amplitudes at frequencies $\pm\Omega$ with respect to the pump. From here, one obtains a generalized Hill's equation:

$$\frac{d^2A}{dz^2} + \frac{a^2}{2\Delta}[\beta_e^2 + \beta_e k_0 n_2 A_0^2 w_i^2 f(z)]A = 0, \qquad (1)$$

where $A(z)$ is related to the c_1, c_2 amplitudes, a is the core radius, Δ is the relative core-cladding index difference, and n_2 is the nonlinear index coefficient. A_0 represents the input field amplitude, $f(z) = 1/w^2(z)$, where $w(z)$ is the periodically varying spot size. Moreover, $\beta_e = [\beta(\omega_0 + \Omega) + \beta(\omega_0 - \Omega)]/2 - \beta(\omega_0)$ stands for the even dispersion function, where only even terms (to all orders) in the dispersion relation are involved.

The response of this MMF system is theoretically analyzed using Floquet theory by determining its corresponding stability diagram (Fig. 1(b)). It should be emphasized that as the power increases, higher-order harmonics from the Fourier series expansion of $f(z)$ have a stronger impact on the boundaries associated with the resulting stability diagram. To observe this behavior, we conducted experiments in parabolic MMFs having different radii. As the number of modes increases, one expects more severe beam focusing effects, hence shifting and widening the GPI sidebands, as predicted by theory (Fig. 2(a)). In our experiments we used two different parabolic fibers having core diameters of $60\ \mu m$ and $80\ \mu m$, and a length of $\sim 5\ m$. In addition, a Q-switched microchip laser at $1064\ nm$ ($400\ ps$, $95\ \mu J$ and $500\ Hz$) with a peak power of $\sim 185\ kW$ was used. The shifting and widening of the GPI sidebands in the measured spectrum (Figs. 2(b) and 2(c)) are in agreement with our analytical predictions.

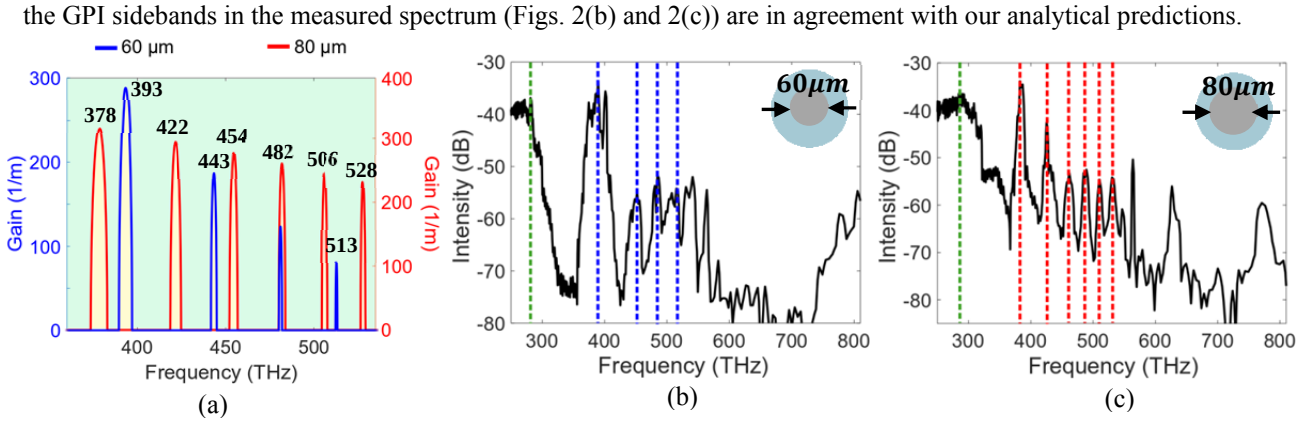

Fig. 2. (a) Gain spectrum associated with two MMFs having $60\ \mu m$ and $80\mu m$ core diameters. Output spectrum from a MMF with (b) $60\ \mu m$ and (c) $80\ \mu m$ core diameter. The green dotted line indicates the pump wavelength ($1064\ nm$), while the blue (red) dotted lines correspond to the blue (red) GPI peaks predicted analytically in (a). The input peak power is $\sim 185\ kW$, and the fiber length is $\sim 5\ m$.

Acknowledgments. ONR (MURI grant no. N00014-13-1-0649), HEL-JTO (W911NF-12-1-0450), ARO (W911NF-12-1-0450), AFOSR (FA9550-15-10041), and NSF (ECCS1711230).

References

[1] G. Lopez-Galmiche, Z. Sanjabi Eznaveh, M. A. Eftekhar, J. Antonio Lopez, L. G. Wright, F. Wise, D. Christodoulides, and R. Amezcua Correa, "Visible supercontinuum generation in a graded index multimode fiber pumped at 1064 nm," Opt. Lett. **41**, 2553-2556 (2016).

[2] K. Krupa, A. Tonello, A. Barthelemy, and V. Couderc, "Observation of Geometric Parametric Instability Induced by the Periodic Spatial Self-Imaging of Multimode Waves," Phys. Rev. Lett. **116,** 183901 (2016).

[3] S. Longhi, "Modulational instability and space-time dynamics in nonlinear parabolic-index optical fibers," Opt. Lett. **28,** 2363-2365 (2003).

[4] M. Conforti, C. Mas Arabi, A. Mussot, and A. Kudlinski, "Fast and accurate modeling of nonlinear pulse propagation in graded-index multimode fibers," Opt. Lett. **42**, 4004-4007 (2017).

[5] C. Mas Arabí, A. Kudlinski, A. Mussot, and M. Conforti, "Geometric parametric instability in periodically modulated GRIN multimode fibers," arXiv:1711.05703 (2017).