

Asymmetric Spectral Noise in Supercontinuum Generation Using PM-ANDi Optical Fibers

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Abstract: Polarization-maintaining all-normal-dispersion fibers are expected to suppress polarization instabilities and enable ultra-stable supercontinuum generation. Here, we show experimentally and numerically that polarization modulation instability can still develop when pumping the slow axis, leading to asymmetric spectral noise and reduced coherence.

Polarization-maintaining all-normal-dispersion (PM-ANDi) optical fibers have become a standard photonic platform for ultra-low-noise supercontinuum (SC) generation [1-3], overcoming the polarization instabilities observed in conventional non-PM ANDi fibers [4]. In standard ANDi fibers, nonlinear polarization coupling and polarization modulation instability (PMI) can strongly degrade spectral coherence, limiting coherent SC generation to pump pulse durations typically below 120 fs [1]. Due to their built-in birefringence, PM-ANDi fibers are generally expected to suppress these vector instabilities and provide stable SC independently of the pumping axis.

In this work, we demonstrate that polarization instabilities can nevertheless persist in PM-ANDi fibers under specific pumping conditions. In particular, we show that pumping along the slow axis (SA) can still trigger residual PMI dynamics, leading to asymmetric spectral noise compared with pumping along the fast axis (FA). Previous studies mainly focused on short pump pulses, for which these instabilities remain weak [1,3], resulting in similar noise properties for both polarization axes. Here, we identify critical pulse-duration thresholds above which the SC stability becomes strongly dependent on the selected principal axis.

The PM-ANDi fiber under test is a commercially available PCF (NL-PM-1050-NEG, NKT Photonics), whose dispersion and birefringence profiles are shown in Figs. 1(a–b). Figure 1(c) compares the experimentally measured and numerically simulated SC generated by pumping the slow axis of a 45-cm-long fiber with 200 fs pulses at 1030 nm and a peak power of 20 kW. Under these conditions, a distinct peak emerges at 1370 nm next to the otherwise broad and flat SC spectrum that extends from 750 nm to 1300 nm. This peak is identified as arising from PMI, as confirmed by numerical simulations of the coupled nonlinear Schrödinger equations (NLSEs) (Figs. 1(d–e)). These simulations reproduce the experimental observations and reveal a Stokes sideband at 1370 nm, accompanied by a corresponding anti-Stokes sideband at 1010 nm within the continuum, both generated on the fast axis. In addition, the measured frequency shift of 38 THz is in excellent agreement with the PMI phase-matching condition [5], obtained by considering the outermost self-phase modulation sideband at 1162 nm as the effective pump. These results clearly demonstrate that residual PMI can persist in PM-ANDi fibers despite their strong birefringence, leading to asymmetric spectral noise within the SC.

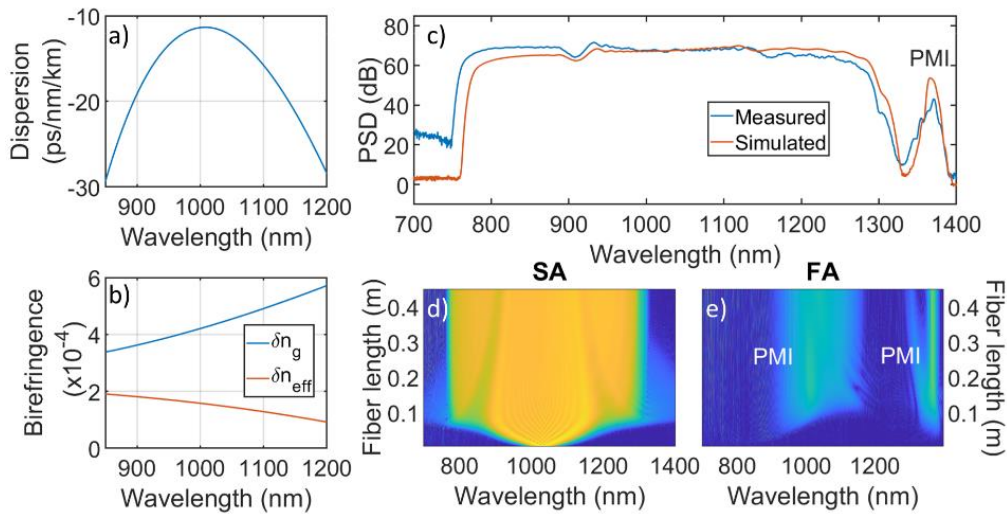


Fig. 1. Fiber properties and comparison between experiment and numerical simulations. (a) Measured dispersion of the PM-ANDi fiber, assumed identical for both polarization axes. (b) Group and phase birefringence as a function of wavelength. (c) Experimental and simulated SC spectra obtained by pumping the slow axis (SA) with 200 fs Gaussian pulses at 1030 nm and a peak power of 20 kW. (d) Simulated spectral evolution of the SC along the slow axis and (e) of the PMI sidebands along the fast axis (FA).

To verify this, we measured the relative intensity noise (RIN) of the spectrally filtered SC using a RIN analyzer and following the method described in Refs. [3,6]. Figure 2(a) compares the measured spectral RIN (in %) for both fiber axes with numerical simulations performed over 30 pulses with independent noise seeds, including quantum noise and an input 0.1% RIN to match the measured pump fluctuations. Two pronounced noise peaks are observed in both experiment and simulation when pumping along the SA (blue curve). The first peak appears experimentally around 1020 nm, close to the anti-Stokes PMI sideband, while simulations reproduce the same feature with a somewhat broader spectral distribution. The second peak, located near 1155 nm, coincides with the estimated effective pump wavelength associated with the PMI process. These results demonstrate that spectral RIN measurements provide a highly sensitive probe of PMI dynamics and can reveal instability sidebands that are not clearly visible in the averaged SC spectrum alone.

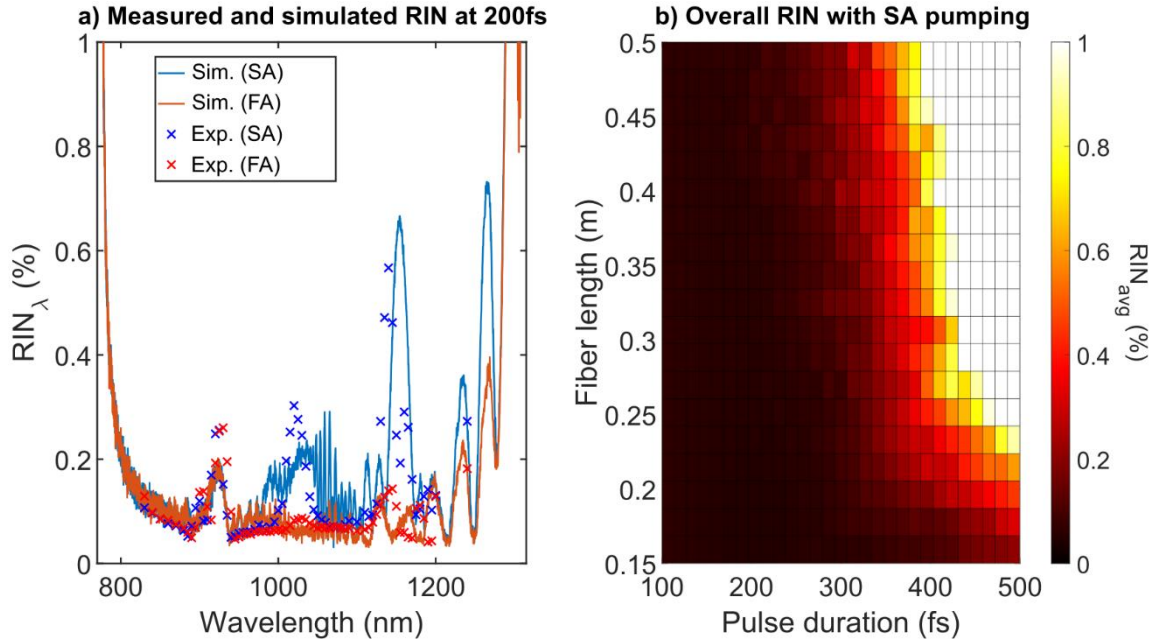


Fig. 2. **Measured and simulated relative intensity noise (RIN).** (a) Experimental and numerical RIN results for 200 fs pulses at 20 kW peak power in a 45-cm-long fiber, shown for both principal polarization axes. (b) Numerical simulations of the average RIN as a function of pump pulse duration and fiber length when pumping along the slow axis (SA) at 20 kW peak power with only quantum noise.

To generalize these results, we performed additional numerical simulations (Fig. 2(b)) exploring a range of pump pulse durations and fiber lengths, and evaluated the average RIN integrated over the SC bandwidth for pumping on the slow axis (SA). The simulations reveal an increase in noise for pulse durations exceeding approximately 250 fs, indicating a clear instability threshold. In contrast, pumping on the fast axis (FA) under identical conditions (not shown) yields behavior consistent with scalar propagation models [7], where the noise is primarily governed by Raman-induced effects and increases significantly only for pump pulse durations exceeding 1 ps.

To conclude, these results demonstrate that noise-resolved measurements provide a sensitive tool for identifying instability mechanisms that may remain hidden in averaged SC spectra. They also establish quantitative operating boundaries in terms of pump parameters, highlighting the critical role of the principal polarization axis in achieving highly stable and coherent supercontinuum generation in PM-ANDi fibers.

References

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