Dual-Wavelength Pumped Supercontinuum Generation and Temporal Reflection Dynamics in a Nonlinear Photonic Integrated Circuit

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ABSTRACT

We demonstrate on-chip supercontinuum generation using dual-wavelength pumping in a nonlinear photonic integrated circuit fabricated from high-index doped silica glass. Femtosecond pulses at 1040 nm and 1560 nm interact through cross-phase modulation and temporal reflections, producing broadband spectra that exceed those from single-pump excitation. Temporal reflections arise when the 1040 nm pulse interacts with a soliton-like index barrier at 1560 nm, generating far-detuned dispersive waves that extend the continuum. Experiments and simulations show excellent agreement with phase-matching theory. These results represent the first demonstration of dual-pump supercontinuum generation on a chip and highlight temporal reflections as a key mechanism for bandwidth control in integrated nonlinear photonics.

Keywords: Nonlinear Optics, Integrated Optics, Supercontinuum generation, Temporal Reflection.

1. INTRODUCTION

Supercontinuum (SC) generation has become a key tool in optical science, enabling applications in metrology, imaging, spectroscopy, and telecommunications.[1–3] While traditionally achieved in optical fibers and bulk media, recent progress in integrated photonics has stimulated strong interest in on-chip SC sources.[4,5] Integrated waveguides offer major advantages, including compactness, low power consumption, and scalability, and have enabled broadband SC generation across a wide range of material platforms, from silica and silicon to chalcogenide and lithium niobate, with spectra extending from the visible to the mid-infrared.[4]

To date, most demonstrations of SC generation in photonic integrated circuits rely on single femtosecond-pulse pumping. However, multi-wavelength pumping schemes provide additional degrees of freedom to tailor nonlinear interactions and potentially enhance spectral broadening.

In this proceeding, we demonstrate on-chip SC generation in a high-index doped silica waveguide using dual femtosecond pumping at 1040 nm and 1560 nm. Through cross-phase modulation (XPM), this approach enables enhanced spectral broadening and improved spectral power density. In addition, we observe signatures of temporal reflections (TR) arising from the interaction between the two pulses, analogous to optical event-horizon dynamics. These reflections generate additional dispersive waves, further extending the SC bandwidth. The experimental results are in good agreement with numerical simulations and phase-matching analysis, highlighting the potential of dual-pump schemes for advanced integrated photonic SC sources.

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2. EXPERIMENT

Dual-pumping schemes have previously been demonstrated in photonic crystal fibers (PCFs), showing enhanced spectral broadening through cross-phase modulation (XPM).[6–8] Here, we employ dual femtosecond pumping at 1040 nm and 1560 nm in a 50-cm-long spiral highly doped silica glass (HDSG) waveguide (Fig. 1(a)). The core dimensions are 1.5 μm $\times$ 1.52 μm with refractive index $n \approx 1.7$ and nonlinear coefficient $\sim$250 $\mathrm{W^{-1}km^{-1}}$ at 1560 nm. Numerical simulations (FEM) show an all-normal to anomalous dispersion profile with three zero-dispersion wavelengths near 1064, 1800, and 2300 nm (Fig. 1(b)). The pump wavelengths are selected near the first ZDW in the normal dispersion regime (1040 nm) and in the anomalous regime near the second ZDW (1560 nm) to enhance nonlinear interactions and enable temporal reflections. The propagation loss is approximately 0.1 dB/cm and the total insertion loss is 8.9 dB (Fig. 1(c)).

The experimental setup is shown in Fig. 1(d). Two synchronized femtosecond fiber lasers are used: a 1560 nm source (70 fs, 50 MHz) and a 1040 nm source (150 fs, 50 MHz). The 1040 nm beam is attenuated to $\sim$200 mW, while the 1560 nm beam is delivered through a polarization-maintaining fiber. Polarization and spatial overlap are adjusted using waveplates and mirrors, and both beams are combined via a dichroic mirror before coupling into the waveguide.

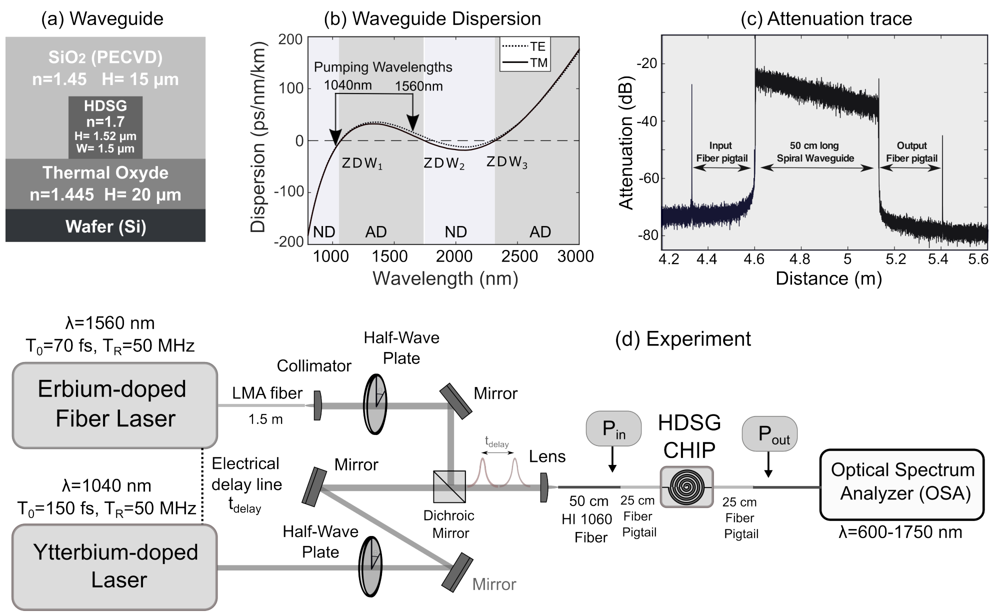

Figure 1. (a) Cross-section of the highly doped silica glass (HDSG) integrated waveguide used for dual-pump SC generation; (b) group-velocity dispersion (GVD) of both TE and TM optical modes; (c) attenuation trace measured with a high-resolution optical time domain reflectometer (OBR Luna); (d) dual-pump experimental setup scheme.

Temporal synchronization is first achieved electronically (tens of ps) and then refined optically by maximizing the SC bandwidth, reaching a precision of $\sim$100 fs. A temporal scan over $\sim$15 ps is performed around zero delay.

3. RESULTS AND COMPARISON WITH SIMULATIONS

Figures 2(a) and (b) present the experimental and simulated output spectra as a function of the relative time delay. As the delay approaches zero, strong XPM interactions induce frequency shifts and temporally localised spectral features. In particular, a new peak emerges around 722 nm (experiment) / 732 nm (simulation), which is attributed to temporal reflections of the 1040 nm pulse interacting with the 1560 nm soliton barrier.[9] The numerical simulations were performed by solving the scalar generalized nonlinear Schrödinger equation (GNLSE), including the two femtosecond pump fields and their relative delay.

In addition, the dispersive wave (DW) generated by the 1560 nm soliton is observed around 710 nm (experiment) / 712 nm (simulation), independently of the delay. Figure 2(c) compares experimental spectra at two

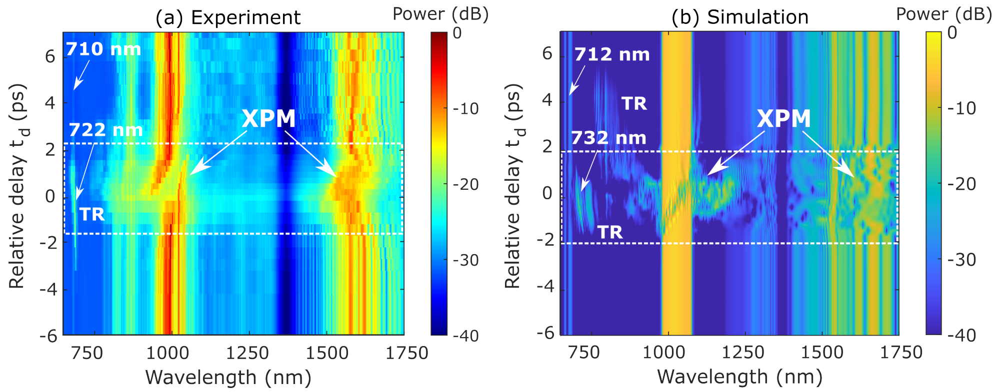

Figure 2. Dual-pumping on-chip SC generation: (a) Experimental and (b) numerical spectra as a function of relative pulse delay, showing XPM-induced wavelength shifts and a temporal reflection (TR) peak at 722 nm (experiment) / 732 nm (simulation).

different delays, highlighting enhanced spectral coverage in the 800–1000 nm range at zero delay, together with the appearance of temporally reflected radiation at 722 nm. Figure 3 compares single- and dual-pump numerical simulations. Single-pump 1560 nm generates a DW at 712 nm. Dual-pump with zero relative delay produces a new peak at 732 nm due to temporal reflection of the 1040 nm pulse against the 1560 nm soliton barrier. This effect arises from four-wave mixing interactions, with the soliton order $N \approx 17$ explaining strong compression and multiple reflections.

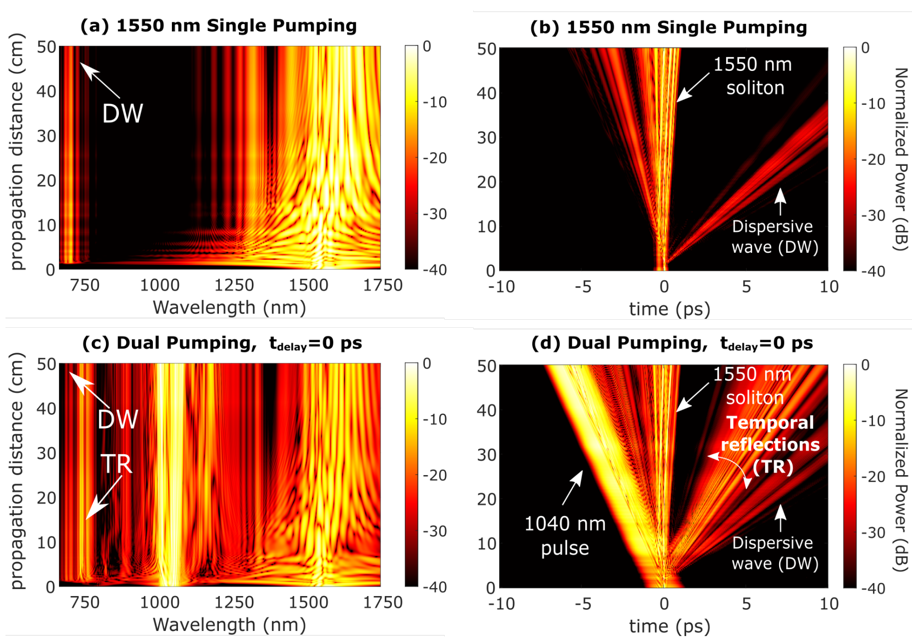

Figure 3. Numerical simulations: Spectral (left) and temporal (right) evolution along the HDSG waveguide. (a,b) Single-pump 1560 nm showing DW at 710 nm. (c-d) Dual-pump showing temporal reflections of 1040 nm at 732 nm for 0 ps delay.

4. PHASE-MATCHING ANALYSIS

Both the DW and TR processes rely on four-wave mixing (FWM) and phase-matching :.[10] The DW wavelength ω_{DW} satisfies the phase-matching equation:[10]

$$\beta(\omega_{DW}) - \beta(\omega_S) - \beta_1(\omega_{DW} - \omega_S) - \gamma P_S/2 = 0, \tag{1}$$

where ω_S and P_S are the soliton frequency and peak power, and γ the nonlinear coefficient. This predicts DW emission at 712 nm, matching both simulations and experiments (Fig. 2).

Temporal reflections satisfy:[11,12]

$$\beta(\omega_{TR} - \omega_S) = \beta(\omega_{1040} - \omega_S), \quad \beta(\omega - \omega_S) = \beta(\omega) - \beta_0 - \beta_1(\omega - \omega_S), \tag{2}$$

where ω_{TR} is the reflected wave frequency. The prediction of $\omega_{TR} \approx 732$ nm aligns with simulations at zero delay. Due to soliton spectral width, Raman shift, and recoil, TR peaks span a range for increasing positive delays, while negative delays show no reflections (Fig. 4).

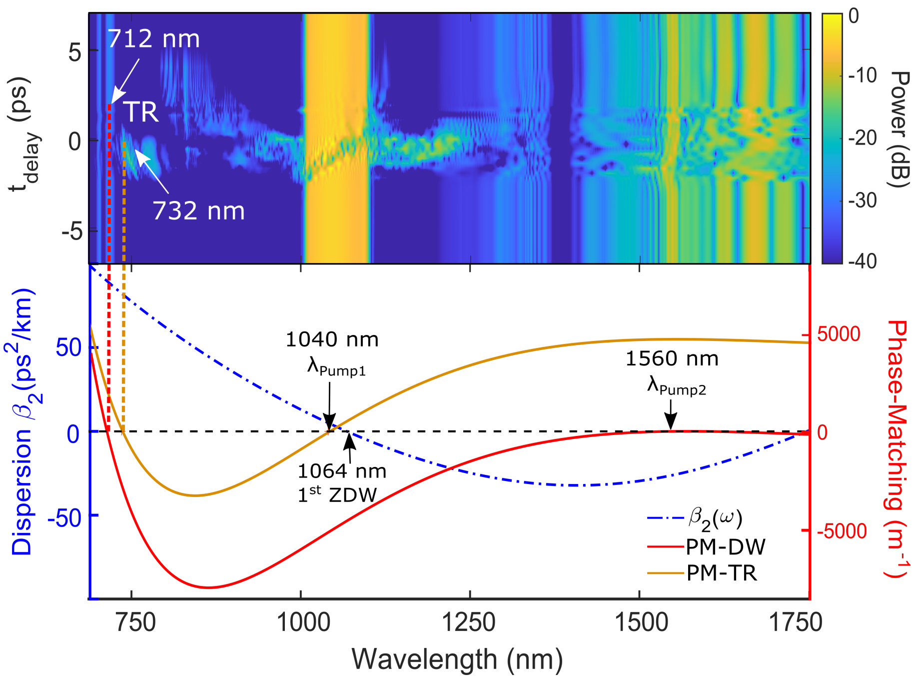

Figure 4. Top: Simulated SC spectra as a function of the relative delay. Bottom: Dispersion curve (blue) and phase-matching conditions for dispersive wave generation from the 1560 nm soliton (red, 712 nm) and temporal reflection of the 1040 nm pulse from the soliton-induced index barrier (yellow, 732 nm).

5. CONCLUSION

We have demonstrated dual-pump supercontinuum generation in an integrated high-index doped silica waveguide and analyzed the effect of relative delays between 1040 nm and 1560 nm pulses. Cross-phase modulation (XPM) and temporal reflections enhance the SC bandwidth, with the 1040 nm pulse reflecting off the 1560 nm soliton barrier, producing distinct spectral features in excellent agreement with phase-matching predictions. Dispersive Fourier transform measurements reveal that SC stability is strongly delay-dependent: full synchronization increases noise, while small relative delays improve stability. These results provide practical guidance for optimizing dual-pump SC sources for advanced integrated photonics applications.

6. ACKNOWLEDGMENTS

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