Supercontinuum generation in high-index doped silica photonic integrated circuits under diverse pumping settings

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Abstract. Recent years have witnessed remarkable progress in enhancing the supercontinuum (SC) generation in highly nonlinear photonic integrated waveguides. In this study, we conduct a comprehensive investigation into supercontinuum (SC) generation in high-index doped silica glass integrated waveguides. We explore a variety of femtosecond pumping wavelengths and input polarization states, demonstrating octave-spanning SC bandwidth from visible to mid-infrared wavelengths.

1 Introduction

Due to their unique combination of high brightness, multi-octave bandwidth, fiber delivery, supercontinuum (SC) laser sources have revolutionized many applications, including optical coherence tomography (OCT), fluorescence imaging, optical sensing, absorption spectroscopy, and optical frequency comb metrology [1,2]. While SC light has been the subject of extensive research and development in optical fibers for over three decades, current focus has shifted towards the development of compact, low-threshold SC sources based on photonic integrated photonic circuits (PICs) [3]. Indeed, the recent technological advances in the design and fabrication of low-loss highly nonlinear integrated photonic chip waveguides are currently driving new research on SC generation in various materials, and yet unexplored regions of the electromagnetic spectrum such as the mid-infrared. SC generation has already been investigated in many integrated and dispersion-engineered photonic integrated circuits based on glasses or wide band-gap semiconductors, such as silica (SiO_2), titanium dioxide (TiO_2), silicon (Si), silicon nitride (Si_3N_4), silicon germanium (SiGe), Aluminum nitride (AiN), chalcogenide glass (As_2S_3), lithium niobate on insulator (LNOI), and more recently, Gallium phosphide (GaP) material [3]. Among those available nonlinear materials, highly doped silica glass (HDSG) is very promising because it has several advantages including both CMOS and silica fiber compatibility, a wide transparency window from 0.3 μm till 3 μm, a nonlinearity greater than pure fused silica, no free carrier or nonlinear absorption. Although SC generation in an HDSG waveguide has already been investigated in the past, the role of Raman scattering, various dispersion pumping regimes, and polarization effects on SC generation hitherto remains elusive.

In this paper, we present new results of SC generation in short and long spiral HDSG chip waveguides under various pumping wavelengths and input polarization states. We observed nearly flat SC spectra spanning from 700 nm to 2500 nm when pumping the waveguide in the anomalous dispersion regime (at 1200 nm, 1300 nm, and 1550 nm), due to soliton self-frequency shift (SSFS) and dispersive wave (DW) generation. Conversely, a narrower SC was obtained when pumping the waveguide in the normal dispersion regime (at 1000 nm) as a result of self-phase modulation (SPM), optical wave breaking (OWB), and the appearance of DW in the anomalous dispersion domain. We also investigated the impact of TE/TM pump polarization modes on SC generation and found good agreement with numerical simulations based on a modified nonlinear Schrödinger equation, including a new Raman response function measured in the high index doped silica glass.

2 Experiment results

Figure 1(a) shows the cross-section of the chip waveguide provided by QXP technologies. It is integrated into silica (PECVD), and deposited on SiO_2 (thermal oxide), all deposited on a silicon wafer. The chip is made up of 20 reversible input/output waveguides, all connected to 25cm-long SMF-28 fiber pigtails, thus facilitating the coupling and extraction of light. For SC generation, we experimentally investigated a short (3-cm) and a long (50-cm) long spiral waveguides. The total insertion loss of

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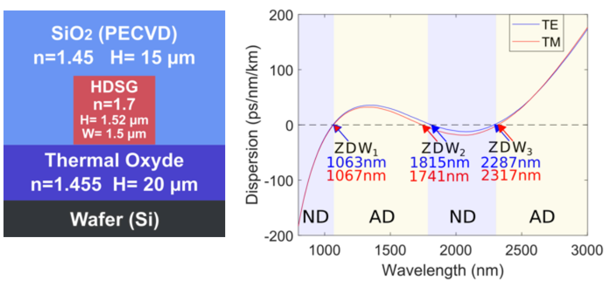

Figure 1 : highly doped silica waveguide cross section and computed group-velocity dispersion versus wavelength for TE and TM modes.

latter has been measured to be 8.9 dB at =1550 nm. Figure 1(b) shows the computed group velocity dispersion (GVD) for the TE and TM modes, using a finite element method (FEM)-based software. Both TE/TM modes exhibit three zero-dispersion wavelengths (ZDW) near 1000 nm, 1800 nm, and 2300 nm, respectively. The birefringence of the waveguide has been estimated to be below 10^{-4} at 1.55 μm.

Experimentally, we used a 200-fs widely tunable optical parametric oscillator (Chameleon Compact OPO-Vis) as the pump laser to investigate SC generation in the chip. Figures 2 display the SC spectra out of the 50-cm long waveguide for three different pumping wavelengths (1550 nm, 1300 nm, 1200 nm) as pump powers increase. As expected, the SC generated across these various pumping wavelengths arises from soliton self-frequency shift within the anomalous dispersion regime, coupled with dispersive wave generation transitioning into the normal dispersion regime. Notably, when employing a pump wavelength of 1550 nm, the resulting SC spectrum spans from 700 nm to well beyond the upper limit of the optical spectrum analyzer (OSA) at 2000 nm (Fig. 2(a)). Consequently, supplementary measurements utilizing a Thorlabs OSA were necessary (See Fig. 2(b)). As can be seen, a discernible SC is evident compared to noise floor,

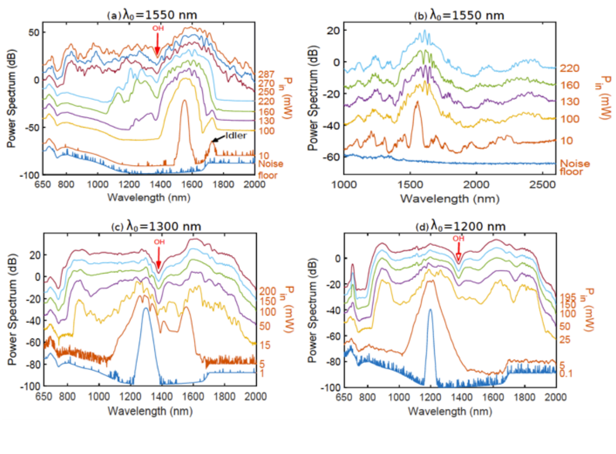

Figure 2 : Experimental SC spectra generated in the 50-cm long QXP chip waveguide for an increasing input mean power, shown on the right side of the graph and for different pumping wavelengths λ0 (1550nm, 1300nm, and 1200nm); (a),(c),(d) were measured with the Agilent OSA while (b) was measured with the Thorlabs OSA.

extending up to 2500 nm. Pumping at 1300 nm and 1200 nm in the anomalous dispersion regime still results in wideband and flatter SC bandwidth, as shown in Figs 2.c-d. We can also observe a clear dip around 1380 nm, which is caused by OH contamination of the QXP waveguide. Pumping at 1000 nm in the normal dispersion regime by self-phase modulation and optical wave breaking was also experimentally investigated, leading to narrower SC extension.

Figures 3(a-d) show a set of numerical simulations of SC generation based on the generalized nonlinear Schrödinger equation (GNLSE), including the OH absorption and a new Raman response function. A quite good agreement is observed between the experimental data shown in Fig. 2 and our simulations. Specifically, when pumping at 1550 nm, the simulated SC spreads from 700 nm to 2500 nm (Fig. 3(a)). Similarly, for a pump wavelength of 1300 nm, the simulated SC also extends from 750 nm to 2000 nm (Fig. 3(b)). The peak observed experimentally at 700 nm when pumping at 1200 nm is also replicated in the simulations, with the SC spanning from 700 nm to 2000 nm (Fig. 3(c)). This peak actually relies on a four-wave mixing (FWM) interaction within the SC.

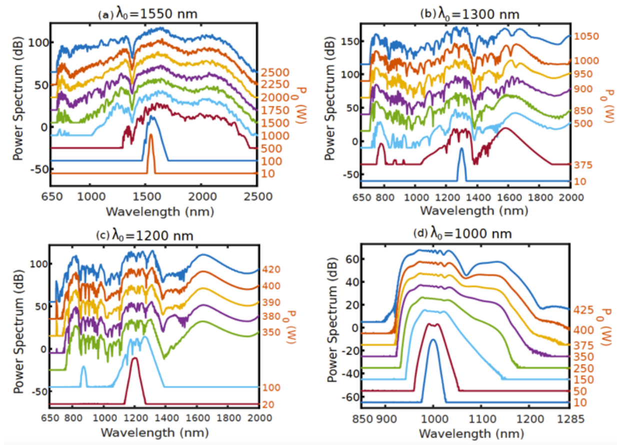

Figure 3: Numerical results: SC generation for different input peak powers P0 shown on the right side of the graph and for different pumping wavelengths λ0.

We also performed a detailed analysis of the polarization and the mutual coherence of the SC generated at different wavelengths (Not shown here).

References

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