Optical event horizon in silicon-on-insulator waveguides

N. Poulvellarie,[1] C. Ciret,[1] and S.-P. Gorza[1]

[1] OPERA-photonics group, Université libre de Bruxelles (ULB), 50 av. F.D. Roosevelt, CP194/5, B-1050 Bruxelles, Belgium

We report on the experimental evidence of an optical event horizon in a nanophotonic waveguide through the reflection of a weak pulse in the telecom C-band on a Near-IR intense pulse at 1850 nm. The experiment takes advantages of the dispersion properties and the large Kerr nonlinearity of the waveguide to generate an optical event horizon. Compared with previous experiments in optical fibers, we have observed an efficient wavelength conversion on centimeter propagation distance at much lower peak power. The reflected pulse wavelength is 13 nm apart from the probe pulse, in agreement with the phase matching condition governing this process.

Introduction

Optical analog of event horizons attract a lot of attention from the scientific community since many years [1–3]. In this process, a weak probe wave propagating in a nonlinear dispersive media is unable to pass through an intense pump pulse despite its slightly different group velocity. This phenomenon can be understood as follows: The propagation of an intense pump in a Kerr medium induces a moving refractive index barrier, which in turn leads to a frequency conversion of the weak interacting probe wave through a cross-phase modulation effect. As the interaction takes place in a dispersive media, the frequency conversion induces a modification of the group velocity of the probe which is either accelerated or decelerated, preventing therefore any crossing between the two waves. The intense pulse refers thus as an horizon which light can neither join nor escape. Potential applications of the optical analog of event horizons to efficient frequency converters [4] or to optical transistors [5] have been pointed out. They are also largely studied for their analogies with the general relativity and in particular to help the experimental observation of the Hawking radiation [2, 6].

Since the first theoretical prediction of optical event horizons [1,7], numerous experimental and theoretical studies have been carried out [8–12]. Due to the essential role played by the dispersion properties of the structure, almost all of these studies consider photonic crystal fibers as the nonlinear dispersive medium, for which quasi on-demand dispersion can be engineered. However, the inherently high power and the long interaction length needed to observe such interactions in optical fibers prevent integrated, low power applications. Recently, the observation of optical event horizons has been reported, with a continuous probe wave (CW), in integrated nanophotonic silicon waveguides [13, 14]. In these structures the absence of the Raman soliton self-frequency shift of the pump as well as the low required pump energy have been recognized as useful for potential applications.

In this paper we report on the demonstration of an optical event horizon in a silicon nanophotonic structure through the interaction of an intense pump pulse with a weak pulsed probe. We show that, in this case, the global frequency conversion efficiency of the probe wave into an idler wave is largely increased compared with previous experiments performed in similar structures with a CW probe. The experimental results are supported by numerical simulations using the generalized nonlinear Schrödinger equation (GNLSE).

Model

The nonlinear interaction between the weak probe and the intense pump pulses with similar group velocities in a Kerr medium can lead to the generation of an idler wave set by the resonant condition [1, 3]:

$$D(\omega_{idler} - \omega_{pump}) = D(\omega_{probe} - \omega_{pump}), \tag{1}$$

in which, the wavenumber $D(\omega - \omega_{pump})$ is the wavenumber of a linear wave at the frequency ω in a reference frame co-moving with the pump at the frequency ω_{pump}. It is defined as $D(\omega - \omega_{pump}) = \beta(\omega) - \beta_0 - \beta_1 \times (\omega - \omega_{pump})$, in which $\beta_0 = \beta(\omega_{pump})$ and $\beta_1 = d\beta/d\omega|_{\omega_{pump}}$. The wavelength dependence of the wavenumber D for the waveguide considered in the experiments is shown in Fig. 1. From this figure, we can infer that, considering a particular probe wavelength, the wavelength of the generated idler wave is located on the other side of the group velocity matching (VM) wavelength, which is the wavelength that propagates with the same group velocity as the pump.

Experimental demonstration and numerical simulations

Our demonstration has been performed in a 1 cm-long, silicon-on-insulator nanophotonic waveguide, with a standard height of 220 nm and a width of 800 nm. The waveguide dimensions have been carefully adjusted in order to tailor its linear dispersion properties (see the inset in Fig. 1) taking the probe and pump wavelengths into account. The probe and the pump pulses are generated by a nondegenerate optical parametric oscillator (OPO, Spectra Physics OPAL) delivering 200 fs pulses at a 82 MHz repetition rate. Their wavelengths are 1850 nm (pump) and 1320 nm (probe). The delay between the probe and the pump pulses is set to enable their interactions within the length of the waveguide. The two beams are combined with a dichroic mirror and then coupled into the waveguide

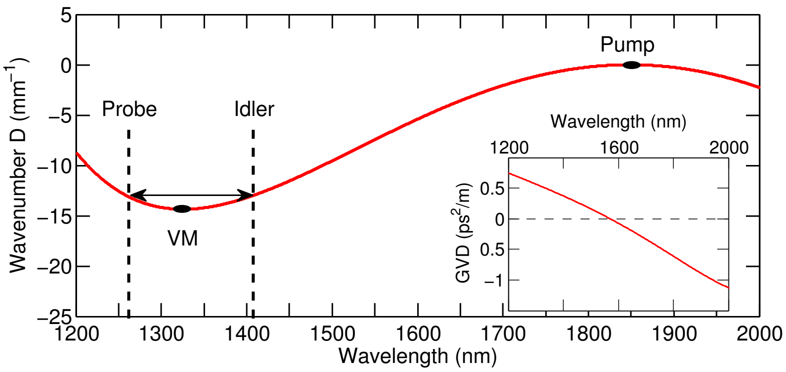

Figure 1: Wavenumber D as a function of the wavelength for a pump wavelength of 1850 nm. The group velocity dispersion (GVD) curve for our 220 nm-thick, 800 nm-wide silicon waveguide is shown in the inset. VM point: see discussion in the text.

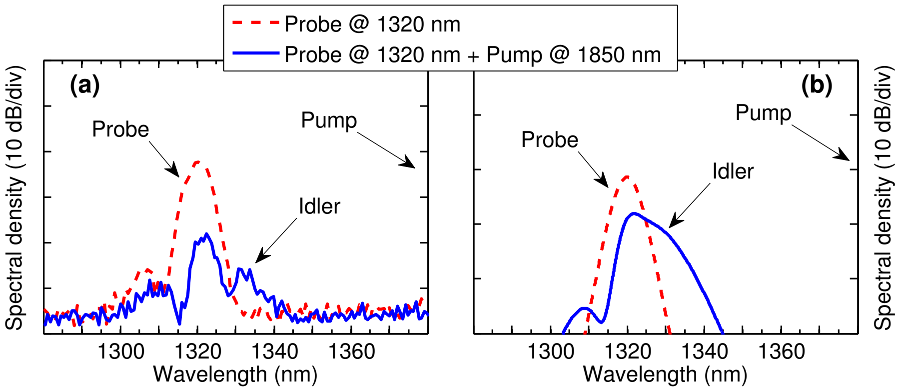

Figure 2: (Color online) Experimental (a) and simulated (b) spectra at the output of the 1 cm-long Si nanowire, recorded around the VM wavelength, without (dashed red) and with (solid blue) the pump pulse.

(TE polarization) using a microscope objective. At the waveguide output, the light is collected by a lensed fiber and sent to an optical spectrum analyzer sensitive in the range 700-1700 nm. The experimental output spectra are displayed in Fig. 2(a) for an on-chip pump and probe peak powers of 500 mW and 10 mW respectively. The pump power has been adjusted to excite a fundamental soliton. This ensures the pump pulse to propagate undistorted. We can clearly observe in Fig. 2(a), that when the pump propagates with a 100 fs delayed probe, there is a net emergence of an idler wave at 1333 nm, associated to a frequency conversion of part of the probe. The idler wave is located on the other side of the VM point as expected from the theory. Its spectral position is in good agreement with the phase-matching equation (1). The experimental results are also in reasonable agreement with the simulations represented in Fig. 2(b). These simulations have been performed by solving the GNLSE :

$$\frac{\partial A(z,t)}{\partial z} = i\sum_{k=2}^{\infty}\frac{i^k}{k!}\beta_k\frac{\partial^k A(z,t)}{\partial t^k} - \frac{\alpha_0}{2}A(z,t) \\ + i\gamma(1+i\tau_{\text{shock}}\frac{\partial}{\partial t})A(z,t)\int_{-\infty}^{+\infty}R(t')\left|A(z,t-t')\right|^2 dt', \quad (2)$$

in which $\beta_k = \partial^k\beta/\partial\omega^k$ are the dispersion coefficients associated with the Taylor series expansion of the propagation constant $\beta(\omega)$ around the pump frequency ω_{pump}. $\alpha_0 = 2\text{dB/cm}$ is the linear loss coefficient. $\gamma = (234+i15)\ \text{W}^{-1}\text{m}^{-1}$ is the complex nonlinear parameter, determined from finite time domain simulations and from literature [15]. The dispersion of the nonlinearity is modeled by the time derivative term in the nonlinear terms, where $\tau_{\text{shock}} = 1/\omega_{pump}$ [16]. Finally, $R(t')$ is the response function accounting for the instantaneous and delayed Raman contributions to the nonlinearity [17].

Conclusion

To summarize, we have demonstrated both experimentally and numerically an optical analog of an event horizon in a silicon nanophotonic waveguide, through the interaction between a weak probe pulse and an intense pump pulse. The experimental results are in reasonable agreement with both the theory and the simulations performed by solving the GNLSE. Numerical simulations have shown that a 200 fs pulse duration, such as in the experiment, is too long to get a high conversion efficiency. However, resorting to 70 fs pulses should allow to achieve conversion efficiencies close to the 99% theoretical limit.

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