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Broadband second harmonic generation of an optical frequency comb produced by four-wave mixing in highly nonlinear fibers

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ABSTRACT

We demonstrate broadband second harmonic generation of low-energy pulses produced by injecting two single-frequency lasers into a highly nonlinear fiber. Full nonlinear conversion of the corresponding spectra, consisting of broadband (∼200 nm) optical frequency combs at ∼1580 nm, were obtained by using conventional birefringence phase-matching in two BIBO crystals (2-mm and 100-μm long) with a normal incidence configuration. The crystals were not tilted and the pulses were not compressed. This broadband conversion results from the large phase-matching bandwidth of the nonlinear BIBO crystals at ∼1550 nm, but also seems to be a consequence of a fundamental comb with small spectral phase variation.

1. Introduction

Broadband combs of highly coherent optical frequencies are generated today by mode-locked lasers. Originally employed to measure optical frequencies [1], they allowed the development of optical atomic clocks [2,3] and several other advances ranging from tests of possible variations of fundamental constants [4], generation of attosecond pulses [5], and phase-sensitive nonlinear optics [6]. Recently optical frequency combs with bandwidths as large as 500 nm at 1550 nm have been produced by nonlinear processes when a continuous-wave (cw) laser is injected into a high-Q silica microresonator [7]. Frequency combs generated by intracavity electro-optic phase modulators have also been known for quite some time, producing bandwidths up to ∼4 THz in the near-infrared [8,9]. Another type of broadband optical frequency comb, still not for metrology applications, can be generated by multiple four-wave mixing (MFWM) when two single-frequency lasers are injected into a highly nonlinear optical fiber (HNLF). Hundreds of equally spaced frequencies can be generated by such "FWM-fiber-combs", spanning a broad spectral region [10]. FWM-fiber-combs benefit from the use of telecom technology, with advantages such as long-term and robust operation, compact sizes and moderate costs.

The motivation of this work was to investigate the possibility of spectral extension of broadband FWM-fiber combs by nonlinear conversion methods. Specifically we explored broadband second harmonic and sum-frequency generation, to convert a comb at 1580 nm into another one at 790 nm, and started by asking whether a full conversion would be possible. Second harmonic or sum-frequency generation (SHG, SFG) between two single-frequency lasers in a nonlinear crystal require only matching of phase velocities, which can be achieved by birefringence or temperature tuning [11]. Quasi-phase-matching is also a common approach, often leading to high efficiencies [12]. For broadband or short pulse light sources, such as femtosecond lasers, corresponding broadband SHG or SFG requires, in addition, matching of the group velocities and group velocity dispersion (GVD) [12]. For ultrashort pulses (<100 fs), with large bandwidths, matching of high-order dispersion terms, such as cubic and fourth order dispersion, is also required. For this reason, thin crystals are usually employed in order to minimize the group velocity mismatch [13], but they also lead to small efficiencies. Even for thin crystals, it is well known that the bandwidth of the second harmonic spectra of short pulse lasers with large spectral bandwidths is usually severely limited by the spectral phase of the fundamental pulses, requiring previous correction (e.g., pulse compression) by proper techniques [14]. Since each generated frequency at $2f$ results from the simultaneous contribution of all frequency pairs symmetrically displaced from f, if the phase varies along the spectrum, each of those pairs will produce its sum-frequency with a corresponding different phase, leading to destructive interference and low output power. Therefore, for low-energy pulses, most broadband nonlinear spectra are generated only after correcting the laser spectral phase [14–19]. In

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particular, Ref. [14] demonstrates a 110-nm bandwidth second harmonic spectrum in the blue region, generated in a 20-μm long KDP crystal directly from a broadband mode-locked laser whose spectral phase had to be corrected in order to produce transform limited pulses.

In this paper, we report what to our knowledge is one of the broadest second harmonic spectra obtained for pulse energies in the nanoJoule range and without any previous spectral phase correction. The spectra consist of discrete wavelengths spaced by ∼0.8–1 nm (∼380–470 GHz), centered at ∼790 nm and with bandwidths of ∼100 nm (48 THz). They were produced simply by focusing into BIBO nonlinear crystals (we use a relatively long, 2-mm crystal, and a shorter 100-μm one), using conventional birefringent phase-matching without tilting the crystals. In addition to the large phase-matching bandwidth presented near 1500 nm [20] by crystals such as BIBO, BBO or LBO [21], a fundamental spectrum with small spectral phase variation ($<\pi$) is also a crucial ingredient in accounting for the broadband nonlinear conversion. We believe that this fundamental light source might result from the use of a short length (∼20 m) of nonlinear fiber, which simply compresses the input "pulse" consisting of the beatnote between the two single-frequency lasers. Our frequency converted, broadband light source at 790 nm can be useful in optical coherence tomography [22] or in applications where great frequency precision or stability is not necessary. In the next sections we describe our setup to generate the fundamental comb and discuss its nonlinear conversion.

2. Broadband combs generated by four-wave mixing in highly nonlinear fibers

Frequency combs generated by MFWM in optical fibers have been studied with a main interest as a source of short pulses at high repetition rates for optical time-division multiplexing in optical telecommunication [23–25]. Recently, such combs with bandwidths as large as 300 nm have been generated using very short (∼3 m) lengths of HNLF [10]. In these combs, two cw, single-frequency pump fields with frequencies f_1 and f_2 (say $f_2 > f_1$), generate Stokes and anti-Stokes waves at frequencies $f_3 = f_1 - \Delta f$ and $f_4 = f_2 + \Delta f$, with $\Delta f = f_2 - f_1$. These new fields undergo parametric gain, which depends on the pump powers, the nonlinear coefficient of the fiber ($\gamma = 2\pi n_2 f / cA_{\mathrm{eff}}$, where $f = (f_1 + f_2)/2$, n_2 is the nonlinear refractive index and A_{eff} is the effective core area of the fiber) and the wavevector mismatch between the four waves ($\Delta k = k_3 + k_4 - k_1 - k_2$) [26]. These new amplified frequencies can in turn generate new ones, in a cascade process known as MFWM [10]. Some of the distinct features of FWM-fiber combs are: (1) the absence of an optical resonator, which gives flexibility in setting and changing the frequency spacing [27], (2) pulsed operation with peak powers of several Watts [10], (3) the possibility of obtaining flat spectral phase, leading to transform-limited (TL) pulses [24], and (4) a fixed pulse-to-pulse phase equal to π arising from the original beatnote between the two input lasers [27].

Fig. 1 shows the experimental setup, similar to that used in Ref. [10], to produce our FWM-fiber-comb. Two commercial, extended-cavity telecommunication semiconductor lasers provided cw, single-frequency output powers of 10 dBm each, and could be tuned through S, C and L-bands, from 1440 to 1620 nm. The two lasers passed through a Mach–Zehnder intensity modulator (IM) which produced pulses typically 40-ns long with low duty cycle (7 μs separation) that were amplified by two cascaded Erbium doped fiber amplifiers (EDFAs, represented as a single one in Fig. 1). The first EDFA is a pre-amplifier with a typical average output power of 15 mW, whereas the second one is a booster with average output power up to 1 W. In our experiments we used peak powers of ∼8 W for each laser. This power was estimated by knowing the pulse duration and duty cycle, and by measuring the attenuated average power, using a photodetector calibrated by a low power continuous-wave laser. The extinction ratio of the peaks was ∼39 dB, the energy contained in each pulse was ∼0.32 μJ, and the energy contained in the noise was <7 nJ.

Due to the pulsed nature of our experiment, stimulated Brillouin scattering (SBS) was not observed. In particular the time between pulses is much higher than the phonon relaxation times. Reported effects such as pulse shape variations or pulse narrowing [28] were not observed during the experiments (the pulse shape was continually monitored). The generated spectra also did not present any noticeable change when the pump linewidths were intentionally broadened by a phase modulator, indicating that SBS was not relevant. The pulses were then sent to two segments of low-dispersion HNLFs (from Sumitomo), and the generated spectrum is analyzed in an optical spectrum analyzer (OSA). The parameters for the first and second fiber segments were, respectively: lengths $L_1 = 15$ m and $L_2 = 5$ m; nonlinear coefficients $\gamma_1 = 15\ \mathrm{W^{-1}\,km^{-1}}$ and $\gamma_2 = 10\ \mathrm{W^{-1}\,km^{-1}}$; zero-dispersion wavelengths $\lambda_{01} = 1570$ nm and $\lambda_{02} = 1530$ nm; dispersion slopes $S_{01} = 0.015\ \mathrm{ps/nm^2/km}$ and $S_{02} = 0.02\ \mathrm{ps/nm^2/km}$. Our fundamental combs at ∼1550 nm are analogous to a mode-locked laser that is also Q-switched. They consist of a train of short pulses, repeating at a few hundred GHz rates (set by the frequency spacing between the input lasers), contained into longer pulses (40-ns long, produced by the intensity modulator), and separated by 7 μs (e.g., repeating at 143 kHz rates).

3. Broadband second harmonic generation

Fig. 1 also shows the simple setup for SHG and SFG, consisting of focusing the output of the HNLF into the nonlinear crystal. We employed a relatively long, 2-mm BIBO crystal and also a shorter

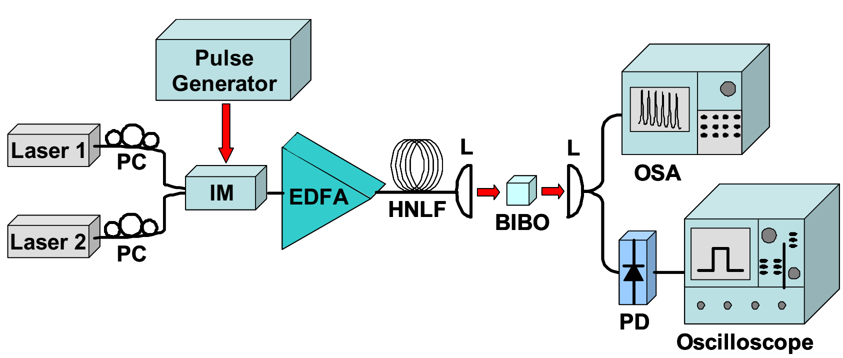

Fig. 1. Experimental setup used to generate an OFC by multiple FWM in a highly nonlinear fiber. Lasers 1 and 2 are standard telecom extended-cavity semiconductor lasers. PC: polarization controller, EDFA: Erbium doped fiber amplifier, HNLF: highly nonlinear fiber; L: lens, BIBO: nonlinear BIBO crystal, PD: photodetector, OSA: optical spectrum analyzer. IM: intensity modulator.