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Experimental generation of an ultra-broad spectrum based on induced-phase modulation in a single-mode glass fiber

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Abstract

An ultra-broad spectrum over the range from 480 to 900 nm is experimentally generated by induced-phase modulation (IPM) of two 120 fs intense optical pulses copropagating in a 3-mm single-mode fused-silica fiber for the first time to our knowledge. The center wavelengths of the two pulses are 640 nm and 795 nm, respectively. The Fourier transform of this spectrum yields a transform limited 4 fs optical pulse. This IPM-induced spectrum broadening method opens the way to monocycle optical pulse generation in the near future. © 1999 Elsevier Science B.V. All rights reserved.

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Ultra-short light pulses are significant tools for time-resolved spectroscopy. The shorter the duration of the pulse, the higher the achievable time resolution becomes. The broad optical spectrum with a well-behaved spectral phase is one of the main prerequisites for short pulse generation because the temporal and spectral characteristics of the pulse electric field are related to each other through the Fourier transform. Self-phase modulation (SPM) in a single-mode glass fiber was demonstrated as the most effective method to generate a broad spectrum. Pulses down to 6 fs were generated in a CPM dye laser-amplifier system in 1987 [1] and recently sub-5 fs optical pulses were generated in a Ti:sapphire cavity-dumped laser system with this technique [2]. Meanwhile, the spectrum broadening based on SPM in a gas-filled capillary waveguide was reported [3] and sub-5 fs intense optical pulses were produced [4,5]. More recently, a diffraction-limited white-light continuum over the range of 400–1100 nm by SPM in a hollow waveguide was demonstrated and a pulse down to 4 fs was generated [6]. However, this performance was obtained by using very short (~25 fs), mJ-level optical pulses through a hollow waveguide. For comparatively longer pulses, a novel method for ultra-broad spectrum generation was proposed by using induced-phase modulation (IPM) of two or three different frequency optical pulses in a glass fiber [7,8]. In this paper, we experimentally report an ultra-broad spectrum generation based on IPM of two intense, comparatively longer femtosecond pulses in a glass fiber for the first time to our knowledge. The induced spectrum which extends from 480 to 900 nm is obtained when two 120 fs, 20 nJ pulses are coupled into a single-mode fused-silica fiber. The Fourier transform of this broad spectrum indicates that a transform limited ~4 fs pulse could be obtained.

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When two optical pulses copropagate inside a nonlinear medium, they can interact with each other through the nonlinearity and phase modulation introduced in each pulse due to the other pulse, which is called IPM. IPM is always accompanied by SPM because the effective refractive index of a pulse depends not only on its the intensity but also on the intensity of the other copropagating pulse. The IPM effect in a picosecond pump-probe configuration was discussed previously [9–11] and just the weak probe-pulse spectrum was broadened by the pump pulse. We consider another case where both optical pulses at different frequencies are the intense pulses. For simplicity, we assume that both pulses are linearly polarized along one of the principal axes of the fiber. The electric field for each pulse ($j=1,2$) can be written as follows [12,13]:

$$\boldsymbol{E}_j(\boldsymbol{r}_j,t)=\tfrac{1}{2}\hat{\boldsymbol{x}}\{F_j(x,y)A_j(z,t)\times\exp[i(\beta_{0j}z-\omega_j t+\phi_{0j})]+\text{c.c.}\}, \tag{1}$$

where $\hat{\boldsymbol{x}}$ is the polarization unit vector, β_{0j} is the corresponding propagation constant at the center angular frequency ω_j, ϕ_{0j} is the initial phase, $F_j(x,y)$ represents the transverse distribution of the fundamental mode, and $A_j(z,t)$ is the slowly varying amplitude. The propagation equation for each pulse envelope $A_j(z,t)$ is derived as follows [12,13]:

$$\frac{\partial A_j}{\partial z}+\beta_{1j}\frac{\partial A_j}{\partial t}+\frac{i}{2}\beta_{2j}\frac{\partial^2 A_j}{\partial t^2}+\frac{\alpha_j}{2}A_j=\frac{in_2\omega_j}{c}\left[f_{jj}|A_j|^2+2f_{jk}|A_k|^2\right]A_j, \tag{2}$$

where $j,k=1$ or 2 and $k\neq j$, $\beta_{1j}=1/v_{gj}$, v_{gj} is the group velocity, β_{2j} is the group velocity dispersion (GVD) coefficient, α_j is the loss coefficient and f_{jk} is a mode overlap integral between the transverse modes of the pulses j and k. The first term in the right-hand side of Eq. (2) represents SPM while the second term is responsible for IPM of the two pulses. It should be pointed out that the group velocity difference between the two pulses plays an important role in IPM because it limits the IPM interaction length. For a pulse of width T_0 (where the intensity becomes 1/e), the walk-off length is defined as:

$$L_w=\frac{T_0}{|v_{g1}^{-1}-v_{g2}^{-1}|}. \tag{3}$$

It is easy to understandd that IPM occurs only over distances $\sim L_w$ irrespective of the actual fiber length L. L_w depends on the relative center-wavelengths and decreases as the center-wavelength difference $\delta\lambda_0$ increases. If the fiber length L satisfies the condition of $L\leq L_w$, the terms on the right-hand side of Eq. (2) show that the IPM effect is two times as large as SPM and a broader spectrum with both IPM and SPM effects than that with SPM alone could be generated. Our experiment is based on this effect.

A schematic of our experimental setup is shown in Fig. 1. The first pulse is generated from a Ti:sapphire regenerative amplifier at 1 kHz repetition rate (Alpha 1000, BMI). The pulse duration is about 120 fs (full width at half maximum, FWHM) with bandwidth of 12 nm (FWHM) centered at 795 nm and the output energy is 750 μJ (henceforth called fundamental pulse). The main output energy from Alpha 1000 is used to generate a continuum wave and pump an optical parametric amplifier (OPA) (Comet-400, BMI). The signal–pulse tuning range in OPA is from 480 to 740 nm with output energy beyond 10 μJ at 1 kHz. The second pulse wavelength is chosen to be 640 nm from OPA and the pulse duration is measured to be about 120 fs (FWHM) with spectral bandwidth of 12 nm (FWHM) (henceforth called signal pulse). Since the continuum wave is generated by SPM of the fundamental pulse under the single-filament condition and is selectively amplified using its second harmonic pulse by optical parametric process with the phase matching condition [14], the phase of the signal wave should have a relation to the phase of the fundamental wave. This condition is critical for generating a stable combined spectrum with IPM in a single-mode glass fiber, which will be confirmed later. From Eq. (3) the calculated walk-off length between the signal pulse and the fundamental pulse is about 2.7 mm. The reason why the second pulse wavelength is selected to be 640 nm lies in that the walk-off length of these two pulses in a fused silica fiber ($L_w=2.7$ mm) is around the length that we are able to cut well (~ 3 mm) and then the IPM effect between the two pulses could be observed clearly. The two pulses are combined by a dichroic mirror, M7, which has high transmission for the fundamental pulse and high reflection for the signal pulse. The optical path of

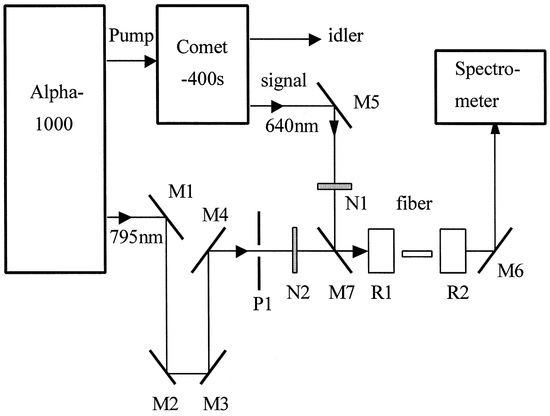

Fig. 1. Schematic of the experimental setup. Alpha 1000 is a 1 kHz regenerative amplifier (BMI), Comet-400s (BMI) is an optical parametric amplifier (OPA) pumped by Alpha 1000 (see text), M1–M6 are aluminum plane mirrors, M7 is a dichroic plane mirror highly transmitting at 795 nm and highly reflecting at 640 nm; P1 is an aperture, N1, N2 are neutral filters, R1, R2 are reflective objectives.

the fundamental pulse is varied by an optical delay stage formed by M2, M3 so that the delay of the two pulses in the fiber can be adjusted. N1 and N2 are variable neutral-density filters and the energies of the two pulses can be controlled independently. The beam size of the signal pulse is about 1.5 mm with a perfect Gaussian distribution and an aperture P1 is added in the fundamental pulse beam to improve beam quality with diameter of around 2.0 mm. The combined two pulses which have the same linear polarizations are coupled into a 3-mm single-mode polarization-preserving fused-silica fiber (Newport F-SPV, 2.7 μm core diameter) by a 36 × reflective objective R1 (Ealing). The advantage of this kind of reflective objective is that no additional GVD is introduced to both pulses because of its reflective components. The coupling efficiency is measured to be around 35% and 40% for the fundamental and signal pulses, respectively. The output from the fiber is collimated by the same type of reflective objective R2 to a wavelength-calibrated spectrometer (SOLAR TII, Ltd., NP250-2) to monitor the output spectrum.

Fig. 2(a) shows the spectra of the input fundamental (solid line) and signal (dashed line) pulses. Fig. 2(b) depicts the spectra of the two pulses with SPM alone at the energy of 20 nJ in the fiber for each pulse. The solid line represents the SPM induced spectrum of the fundamental pulse and the dashed line represents the SPM induced spectrum of the signal pulse. From Fig. 2(b) we observe the separated spectra for the two pulses with only the SPM effect at 20 nJ energy levels. When the two pulses are launched simultaneously into the same fiber with an optimum initial delay between the two pulses (two pulses meet at the center of the fiber, to be discussed later), because of the IPM effect of the two pulses, the two spectra meet each other. We have observed that the output spectrum is significantly stable including the overlapping part. This means that the phase of the spectral-broadened fundamental wave and the phase of the spectral-broadened signal wave have some relation. Accordingly, the output spectrum is constructively synthesized. The optimized spectrum all over the range from 480 to 900 nm is measured (Fig. 2(c)). The pulse energy measured after fiber propagation is about 40 nJ. The shortest pulse attainable by phase correction of this ultra-broad spectrum is obtained by the Fourier transform of the spectrum of Fig. 2(c) assuming a constant spectral phase. This yields the pulse duration of ~ 4 fs (Fig. 2(c) inset). It should be noted that a well-behaved spectral phase of the generated broad spectrum is significant for bandwidth-limited-pulse generation. A rapidly varying phase over the pulse spectrum means that high-orders of spectral phase distortion exist. Even though quadratic and cubic spectral phases can be compensated for by using a prism pair [15], a grating pair [16] and chirped mirrors [17,18], more than forth-order spectral phase compensation becomes very hard using these devices. Fortunately, our calculations by solving Eq. (2) show that a quasi-linear chirp is produced by IPM of the two optical pulses copropagating in the fiber if all parameters are optimized [7,8]. On the other hand, a recently-developed adaptive pulse-compression method using a liquid-crystal spatial light modulator (SLM) has demonstrated that it has the potential to compensate for almost-arbitrary spectral phase distortions [19]. Therefore, it is expect that a sub-5 fs optical pulse will be generated by applying this adaptive compressor.

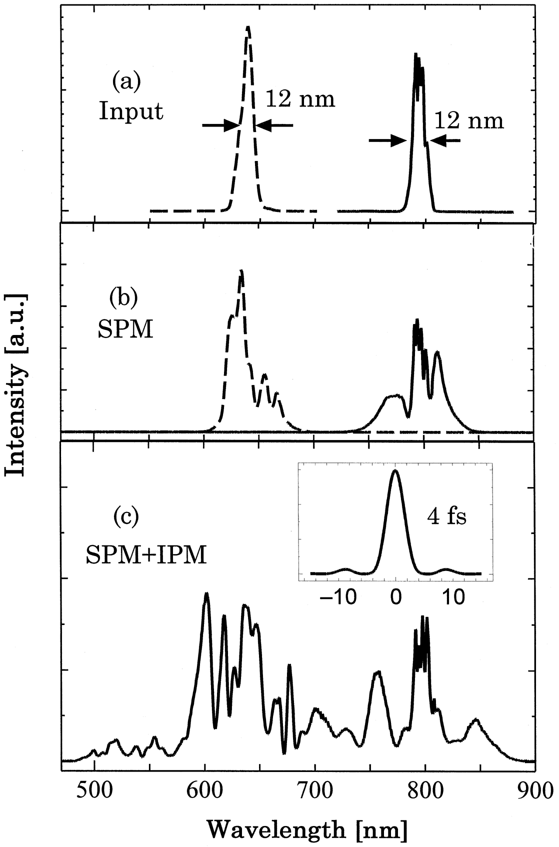

Fig. 2. (a) The spectra of the input fundamental (solid line) and signal (dashed line) pulses; (b) The measured spectra induced by SPM in a 3-mm single-mode fused-silica fiber. The solid line represents the fundamental pulse spectrum by SPM and the dashed line represents the signal pulse spectrum by SPM at the pulse duration of 120 fs, energy of 20 nJ in the fiber for each pulse; (c) The measured spectrum induced by IPM of the two pulses, the same parameters as in (b), the initial time delay between the two pulses is chosen so that the two pulses meet at the center of the fiber. The Fourier transformed pulse intensity is shown in the inset.

Because of the group velocity difference between the two optical pulses propagating in the fiber, they travel at different speeds and after some distance propagation they are separated. We measured the IPM-induced spectra with different initial time delays between the two pulses. The results are shown in Fig. 3. The initial time delay between

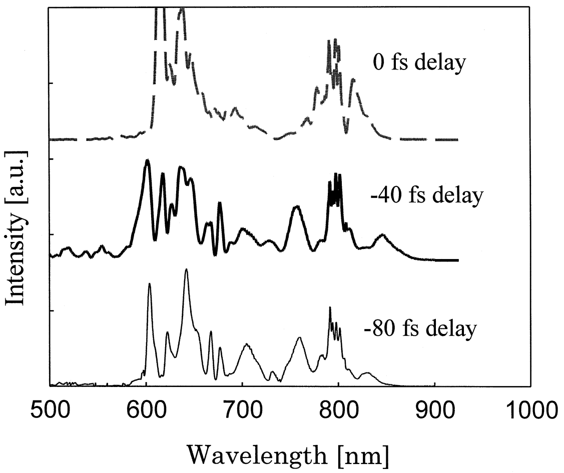

Fig. 3. The measured spectra induced by IPM for the two pulses with different initial time delays under the same parameters as in Fig. 2. The thicker solid line represents the spectrum when the two pulses meet at the center of the fiber, the dashed line represents the spectrum when the two pulses meet at the entrance of the fiber and the thinner solid line represents the spectrum when the two pulses meet at the end of the fiber.

the two pulses $\tau = 0$ fs represents that the two pulses coincide at the fiber entrance (dashed line), and the delays $\tau = -40$ fs and $\tau = -80$ fs represent that the two pulses meet at the center (thicker solid line) and the end of the fiber (thinner solid line), respectively. Our results qualitatively agree with the results reported by Baldeck et al. [20] in which the induced-frequency shift of one weak pulse was observed when another strong picosecond pulse was copropagated with its weak pulse in a 1-m-long single-mode glass fiber. In our case, when the two pulses meet at the entrance of the fiber ($\tau = 0$ fs), because the fundamental pulse travels faster than the signal pulse in the fused-silica fiber, the leading edge of the signal pulse interacts with the trailing edge of the fundamental pulse. As a result, the signal pulse has IPM-induced positive chirp and the fundamental pulse has IPM-induced negative chirp. This leads to larger modulation of the signal pulse spectrum at shorter wavelengths and larger spectral modulation of the fundamental pulse at longer wavelengths. A larger gap between the two spectra is observed in this case (Fig. 3, dashed line). On the contrary, when the two pulses meet at the end of the fiber ($\tau = -80$ fs), the trailing edge of the signal pulse mainly interacts with the leading edge of the fundamental pulse. As a result, the IPM induced spectrum of the signal pulse shifts towards its longer wavelengths and the IPM-induced fundamental pulse spectrum shifts to shorter wavelengths and larger overlap of the two pulse spectra is observed (thinner solid line in Fig. 3). It is found that when the two pulses meet at the center of the fiber, the fundamental pulse passes through the signal pulse in a symmetric manner. As a result, the spectra are broaden by the IPM effect to shorter and longer wavelengths simultaneously for both pulses and the broadest combined spectrum is generated (thicker solid line in Fig. 3). This case is referred to as the optimum initial time delay which we mentioned above. Note that an even broader spectrum could be expected by tuning the second pulse to shorter wavelength, and utilizing a shorter optical fiber owing to the walk-off length L_w depending on the relative wavelengths and decreasing as the center wavelength difference $\delta\lambda_0$ increases.

In summary, ultra-broad spectrum generation based on IPM of two optical pulses copropagating in a single-mode fused-silica fiber has been experimentally demonstrated. In the experiment, two 120 fs pulses with wavelengths at 640 and 795 nm, respectively, have been coupled into a 3-mm single-mode fiber. At pulse energy of 20 nJ coupled into the fiber for both pulses, an ultra-broad coherent spectrum induced by IPM which covers the range from 480 to 900 nm has been generated. The Fourier transform of the spectrum can yield a ~ 4 fs transform limited pulse. This IPM technique can also be applied to high energy ultrashort pulse generation using a gas-filled hollow fiber as a nonlinear medium [21]. It opens a way to generate a single-cycle high energy optical pulse in the near future.

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