Asynchronous encrypted information transmission with sub-6 fs laser system at 2.12 GHz repetition rate

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Abstract: The asynchronous transmission (encoding and decoding) of 64-bit information using binary spectral phase shaping is demonstrated. The accurate introduction and retrieval of the binary information is possible by using multiphoton intrapulse interference phase scan (MIIPS) to measure and correct the spectral phase distortions of the laser and the transmission media. Experimental demonstration is achieved using a sub-6 fs Ti:Sapphire laser with 2.12-GHz repetition rate and an adaptive phase control system.

OCIS codes: (320.7090) Ultrafast lasers; (320.7110) Ultrafast nonlinear optics; (320.7100) Ultrafast measurements; (320.5540) Pulse shaping.

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1. Introduction

Mode-locked femtosecond lasers with repetition rates in the gigahertz range [1] have proved to be a key element in high-precision optical frequency metrology. In the recent decade, improved atomic clocks [2], direct measurements of frequencies of several hundred terahertz with 17-digit accuracy [3], and phase sensitive nonlinear optics experiments [4] have all been demonstrated. The high repetition rate of this kind of laser systems can also be applied in rapid high-resolution spectroscopy, real-time microscopy imaging with nonlinear processes, e.g. second- and third-harmonic generation microscopy, two-photon fluorescence microscopy and coherent anti-Stokes Raman scattering microscopy. The high repetition rates are also advantageous for rapid telecommunications with encryption, especially when the laser system has a broad spectrum. In this paper, we present a sub-6 fs Ti: Sapphire laser system at 2.12 GHz repetition rate with adaptive phase control that has great potential applications in all of the previously mentioned fields. In section 3 we demonstrate the potential use of this laser system in rapid telecommunication applications.

The Ti: Sapphire oscillator used has a prismless four-mirror bow-tie ring cavity configuration to achieve the high repetition rate (Fig. 1). It consists of two curved mirrors with broadband high reflecting (HR) coatings and 3 cm radius of curvature (ROC), a HR chirped convex mirror with 1m focal length (FL), and a flat output coupler (2% transmission), with a similar configuration to that described in references [5, 6] All mirrors inside the cavity are chirped except the output coupler. The laser provides 0.5 nJ pulses at 2.12 GHz repetition rate with a spectrum spanning ~400 nm (dashed curve in Fig. 3) and is extremely stable when mode-locking is achieved. In a set of experiments described later in this paper, it was operated continuously for more than 22 hours.

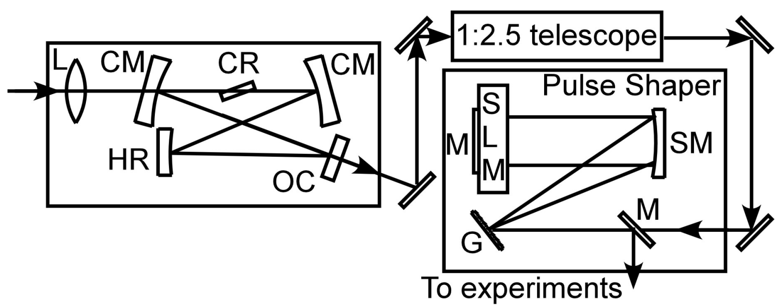

Fig. 1. Schematic optical setup of the laser system. The laser cavity is shown inside the box on the left. L: lens (FL 3cm); CM: chirped curved mirror (ROC 3cm); CR: Ti: Sapphire crystal; HR: high reflection chirped convex mirror (FL -1m); OC: output coupler. The pulse shaper is shown in the lower-right box. G: grating, SM: spherical mirror, M: mirror and SLM: spatial light modulator.

2. Spectral phase control

In order to adaptively control the phase of the laser, the pulses were directed to a grating-based pulse shaper. The laser pulses are first dispersed into different frequency components by a grating and then focused by a spherical mirror onto the spatial light modulator (SLM), that controls the phase of the laser pulses. The laser is then retroreflected onto the same spherical mirror and grating so that the different frequency components recombine. Both the SLM and grating are at a focal distance of the spherical mirror. The optical setup is very similar to the one described in reference [7] with more detail. Multiphoton intrapulse interference phase scan (MIIPS) [8, 9] was employed to obtain transform-limited pulses. Briefly, MIIPS is a single-beam method based on multiphoton intrapulse interference [10, 11] able to both measure and correct the spectral phase of the laser pulses. The measurement is achieved by successively introducing a set of reference phase functions to the laser pulses through the pulse shaper and monitoring the second-harmonic generation (SHG) or other nonlinear optical (NLO) spectra corresponding to each reference phase. The reference phases

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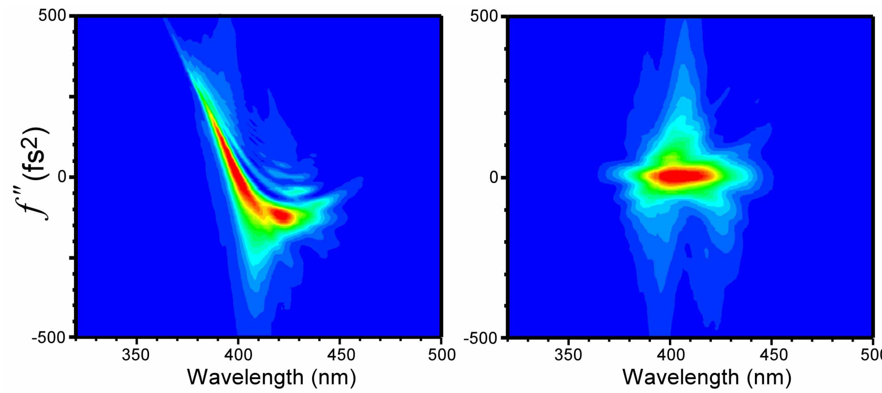

Fig. 2. Experimental MIIPS traces. The left and right panels correspond to the phase-distorted and to the phase compensated pulses (TL), respectively.

that can be used include, but are not limited to, sinusoidal [8, 9], quadratic [12] and cubic phase functions. In this paper we used quadratic phase functions $f(\omega, p)=1/2 * p \ (\omega - \omega_0)^2$, where p is the scanning parameter. When the corresponding SHG spectra are plotted as a function of the scanning parameter, the second derivative of the spectral phase is directly obtained in the MIIPS trace [12], as shown in Fig. 2, where the MIIPS traces with and without spectral phase correction are shown in the right and left panel, respectively.

The spectral phase of the laser pulses is obtained upon double integration of the MIIPS traces. A negative function of the measured phase is then introduced by the pulse shaper in order to compensate the measured phase distortion. A number of such measurement-compensation iterations may be necessary to achieve TL pulses if the phase distortion is large, e.g. over 100 rad. The lower panel of Fig. 3(a) shows the spectrum (dashed line) and the measured spectral phase (solid line) of the laser system, which includes the phase accumulated in the round-trips in the cavity and the phase distortions introduced by the optics. This measured phase corresponds to the left panel of Fig. 2. The residual phase after five MIIPS iterations is shown in the top panel of Fig. 3(a). This residual phase corresponds to the left panel of Fig. 2. With such a residual phase, the calculated time duration of the pulses is

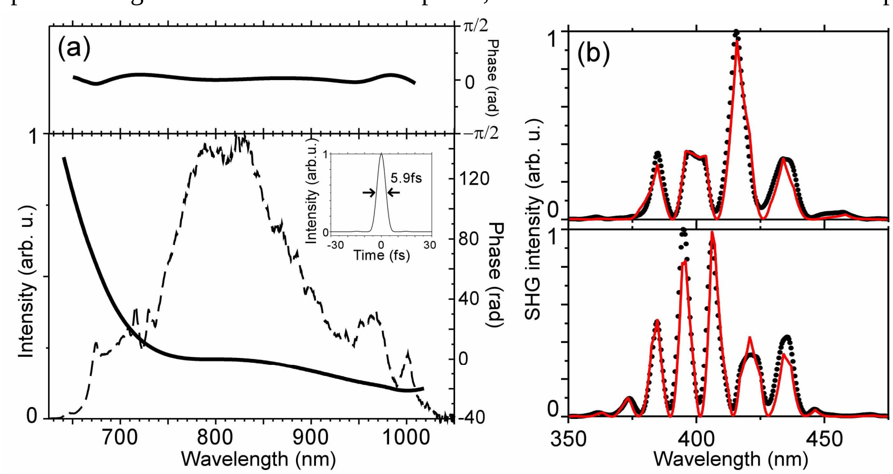

Fig. 3. Spectral phase control. (a) Spectrum (dashed line) and measured spectral phase (solid line). The inset shows the calculated temporal profile. The top panel shows the residual phase after the spectral phase of the system was corrected by MIIPS. (b) Experimental (black dots) and calculated (red line) SHG spectra corresponding to two different 8-bit binary phases. Note the excellent agreement between calculations and experiments.

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~5.9 fs, which would be the shortest pulses at GHz repetition rate to the best of our knowledge [6].

After transform-limited pulses were achieved, a series of 8-bit binary phases defined in the frequency domain, *i.e.*, only containing 0 and π values, were imposed to the pulses. Figure 3(b) shows the experimental and calculated SHG spectra for two different 8-bit binary phases. The excellent match between the experimental and calculated SHG spectra provides an additional proof that the initial spectral phase distortions were accurately measured and corrected. Without the spectral phase correction described in this section, it is impossible to accurately deliver the binary phase information accurately, i.e. impossible to get the agreement between experiments and calculation demonstrated in Fig. 3(b).

3. Adaptive binary phase shaping for encrypted information transmission

One of the most important prospective applications of this laser system that takes advantage of its high repetition is fast information transmission for telecommunications. Here we propose and experimentally demonstrate a simple approach to accomplish 64-bit encrypted information transmission using this laser system. As shown in Fig. 4(a), the sender first translates the information into 64-bit binary phases and then imposes them to the laser pulses through the pulse shaper. The receiver only needs to generate SHG or other NLO spectra from those pulses and then compare the measured spectra with standard spectra stored in a database to retrieve the binary phases, exploiting the fact that a certain binary phase produces a unique SHG spectrum. When encryption of the information is necessary, the sender adds a 64-bit binary key onto the 64-bit information binary information. As a result, unless the receiver knows the encryption key and cancels the encryption through his pulse shaper, the SHG or other NLO spectra generated from the received pulses will not lead to the correct information (see Fig. 4(b)). Weiner and coworkers [13] demonstrated encoding and decoding with femtosecond pulses using M-sequence 20 years ago. In their demonstration, the receiver had to be synchronized with the sender to receive the information properly. In our scheme, such synchronization is not necessary. The receiver only needs to record the NLO spectra of the pulses to retrieve the information, based on correlations with the existing reference library and encryption key.

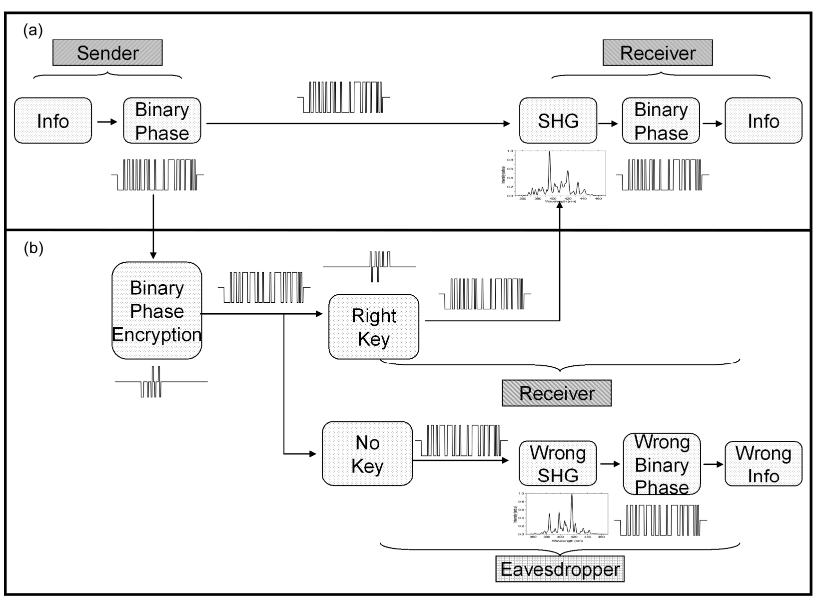

Fig. 4. Concept of information transmission and retrieval using binary phases. (a) Without encryption, (b) with encryption.

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A set of experiments was carried out to prove the feasibility of the concept described above. The experiments shown in Fig. 3 demonstrate that the binary phases can be accurately imposed on the pulses through the pulse shaper provided that MIIPS is used to correct the spectral phase distortions of the laser system and the transmission medium. The next step is to establish a way to retrieve the binary phase from the corresponding SHG spectrum. Figure 5(d) illustrates the SHG spectrum corresponding to binary phase 5(a), and Fig. 5(f) shows the SHG spectrum corresponding to binary phase 5(c), which is the original binary phase 5(a) plus an encryption binary phase 5(b). One can clearly see the difference between those two SHG spectra. Figure 5(e) shows the cross-correlation between two independent measurements of the SHG spectrum corresponding to 5(a) (each spectrum was normalized on itself). Note that the cross-correlation is very symmetric and have an intense peak in the center. When the cross-correlation is performed between SHG spectra corresponding to two different binary phases there is no such symmetry, e.g. 5(g) is the cross-correlation between 5(d) and 5(f). Therefore, we can use this symmetry property of the cross-correlation to retrieve the binary phase carried by the pulses comparing the SHG spectrum generated with reference spectra in a database.

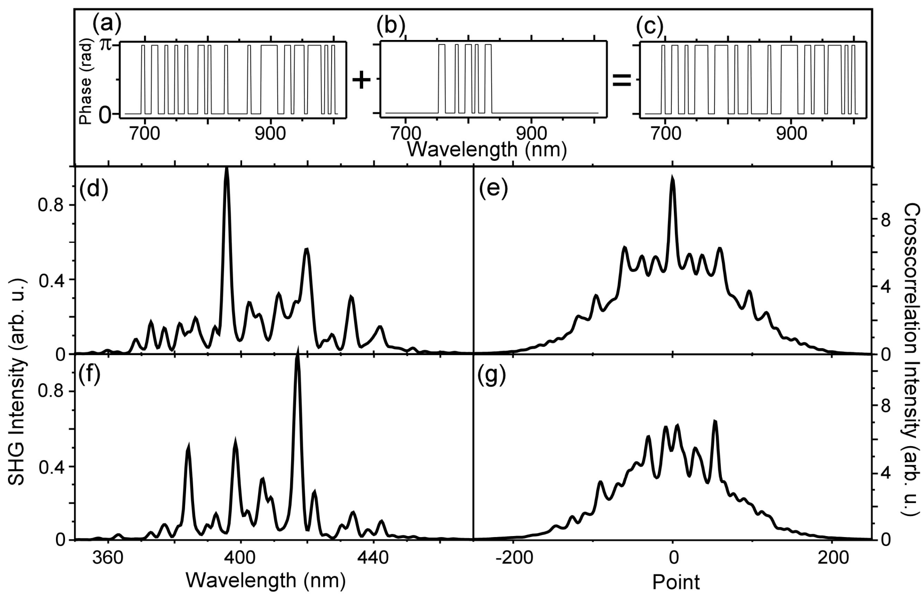

Fig. 5. SHG spectra and their cross-correlations. (a), (b) and (c) illustrate the 64-bit binary phase information, the encryption binary phase and the sum of the first two, respectively. (d) and (f) show the SHG spectra resulting from (a) and (c), respectively. (e) shows the cross-correlation between two SHG spectra corresponding to the same binary phase 5(a), but measured in two different days. (g) shows the cross-correlation between SHG spectra corresponding to different binary phases (d) and (f).

A fitness function, the cross-correlation symmetry factor (CSF), was defined as the difference between the sum of the left half and the sum of the right half of the cross-correlation. Ideally only when the CSF is zero, the measured SHG spectrum matches a stored reference spectrum and the carried binary phase can be retrieved.

We randomly picked more than 25,000 64-bit binary phases as our information and recorded the corresponding SHG spectra as the reference spectral database. We then delivered ~1,000 of those binary phases to the laser pulses and recorded the corresponding SHG on a different day. CSF's between the measured SHG spectra and all of the spectra in the reference database were calculated. In Fig. 6 we randomly picked 3 out of those 1,000 information phases to show that the CSF can be used for retrieving the binary phase information reliably. Although CSF is a non-zero value even when the two spectra correspond to the same binary phase due to the experimental noise, we demonstrated that the CSF has always the smallest

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value when the binary phases match (Fig. 6). Therefore, one can retrieve the corresponding binary phase from the measured SHG spectrum by finding the smallest CSF value.

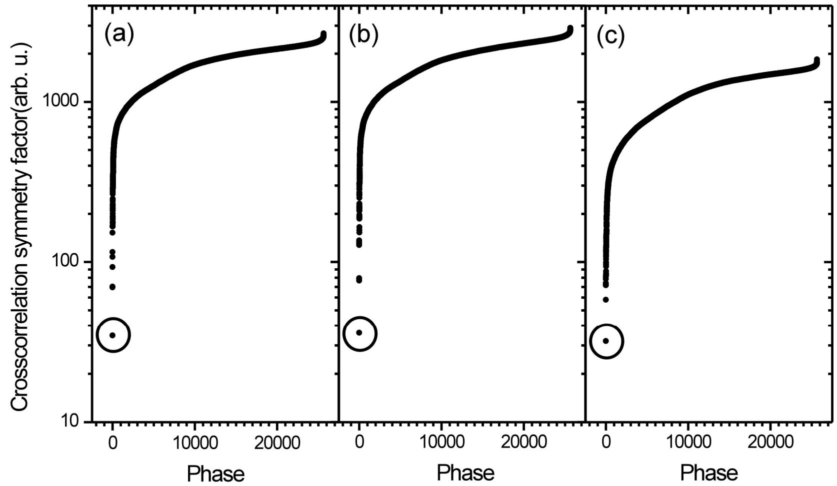

Fig. 6. The CSF for three different randomly picked measured SHG spectra as a function of all the spectra in the reference database, in each case sorted by increasing CSF. Note that the CSF always has the smallest value (circled point) when the cross-correlation is performed between the SHG spectra of corresponding binary phases. Even when one out of 64 bits is different, corresponding to small CSF values, the information can be distinguished.

4. Discussion and conclusion

Ideally, each pulse from the laser system described above can convey a 64-bit encrypted binary phase, resulting in the highest possible information transfer rate of ~2.12 GHz. In our current system the information transfer rate is ~30 Hz because it is limited by the update speed of the spatial light modulator in the pulse shaper. However, phase modulators with much faster update speeds (~100 KHz) already exist [14] and efforts are underway to continue increasing this speed by orders of magnitude [15]. Another possible speed limiting factor would be the current way to retrieve the binary phase from the SHG spectrum by using the CSF value. However, a number of steps based on the appearance of the SHG spectra and the total SHG intensity can be designed to greatly speed up the search procedure.

In conclusion, sub-6fs laser pulses with 2.12 GHz repetition rate were obtained by measuring and compensating the spectral phase with MIIPS. We proposed an approach to achieve rapid encrypted information transmission for telecommunication applications using this laser system and demonstrated the feasibility of the approach experimentally.

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