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Temporal cloak with large fractional hiding window at telecommunication data rate

Feng Zhou, Jianji Dong*, Siqi Yan, Ting Yang

Wuhan National Laboratory for Optoelectronics & School of Optical and Electrical Information, Huazhong University of Science and Technology, Wuhan 430074, China

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A B S T R A C T

We design and experimentally investigate a temporal cloak scheme using ultrashort pulse compression and time-domain Fraunhofer diffraction. An input continuous-wave probe beam is compressed to ultrashort pulse train based on self-phase modulation effect and chirp compensation using single mode fiber. Accordingly, wide temporal gaps appear to act as the cloaking windows. The train of ultrashort pulses can be converted to continuous wave after experiencing enough dispersion, indicating that the temporal gaps are closed. Thus, any time events will be hidden in the temporal gaps from observers. In our study, we demonstrated a temporal cloak system, which is able to hide 88% of the whole time period and cloak pseudorandom digital data at a bitrate of 10 Gbit/s. The relationships of cloaking window fraction versus pump power and the condition of cloaking off are also investigated. These results present a new feasible way towards obtaining a high-fractional cloaking window at telecommunication data rate and hiding real-world messages.

1. Introduction

Temporal cloak is a newborn concept extended by spatial cloak based on space-time duality [1]. The temporal cloak does not create a 'void' to conceal objects in spatial cloak, but open and close a 'gap' to hide events in time-domain [1–7]. Because events that require to be hided are always of great importance, such as switching information over data sequence packets, confidential data, and so forth [8,9]. Temporal cloak is attracting great interests due to its potential applications in the data centers and optical fiber communications [8,9].

Previous temporal cloak schemes were proposed and designed by Fourier analysis method [10,11], atomic system [12,13], space-time version of Maxwell's fisheye lens [14,15], polarization bypass [16], accelerating wave packets [17], and electro-optic photonic crystals [18]. However, these ideas always require bulky and strict system. To simplify the system, efforts have focused on optical fiber communication system. Due to the dominant advantages of optical fiber dispersive device for creating gaps, optical fiber links are promising to become the mainstream of the temporal cloak. Particularly, the first experimental demonstration of temporal cloak was implemented in an optical fiber communication system, which is based on a pair of split time lens using four-wave mixing, and achieves a fractional cloaking window of around 10^{-4} percent at repetition frequency of 41 kHz [19]. However, the fraction of cloaking window and repetition rate are too low for optical fiber communication. To improve its potentials in optical fiber communication system, an effective temporal cloak is implemented by exploiting temporal Talbot effect, which hid 46% of temporal period and succeeded in cloaking pseudorandom data at a bitrate of 12.7 Gbit/s [20]. However, the proportion of concealing window is still not large enough in this cloak scheme. Therefore, it is still challenging to realize a temporal cloak with large fractional hiding window at telecommunication data rate.

In this paper, we experimentally demonstrate a temporal cloak scheme with high fractional hiding window for concealing pseudorandom digital data at a bitrate of 10 Gbit/s. Analogy to the principle of paraxial ray optics cloaking, we combine the temporal pulse compression in highly nonlinear fiber (HNLF) and the temporal Fraunhofer diffraction. A train of ultrashort pulse train is generated to form the time gap with hidden events. The train of ultrashort pulse is then converted to continuous wave (CW) by time-domain Fraunhofer diffraction in order to close the time gaps. The cloaking window fraction can be as high as 88%. The proposed scheme is significant in high-speed communication system due to its large hiding window at telecommunication data rate.

2. Principle and simulation

Similar to the ideal paraxial ray optics cloak that makes light rays

* Corresponding author.
E-mail address: jjdong@mail.hust.edu.cn (J. Dong).

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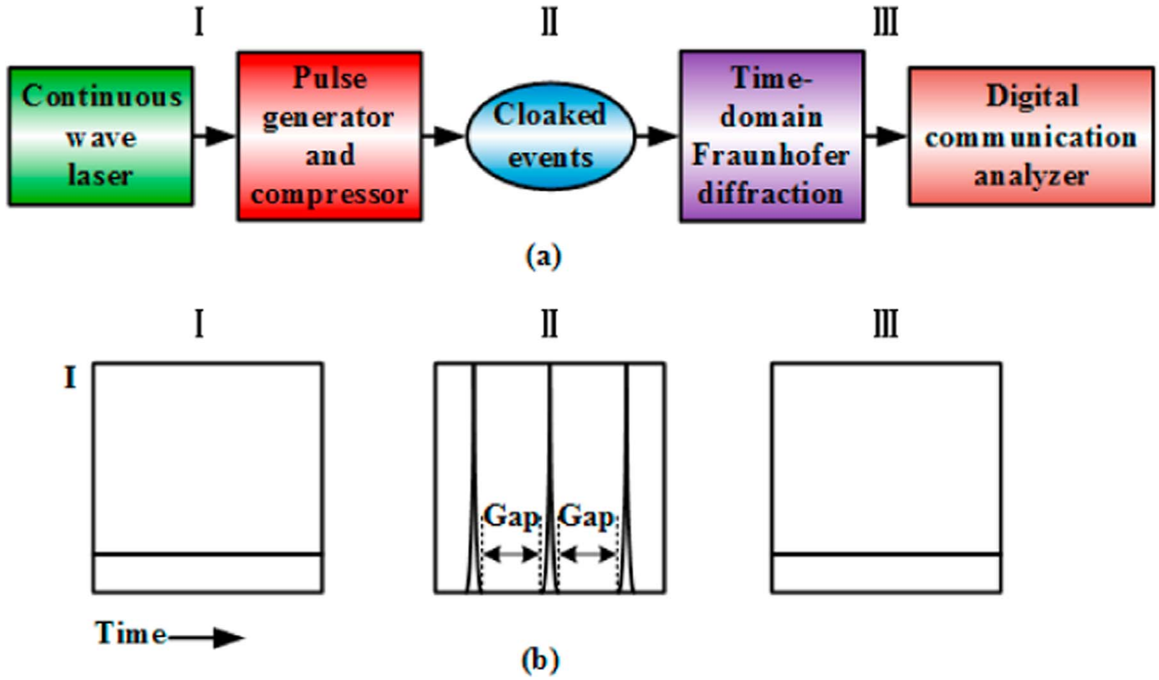

Fig. 1. Schematics of temporal cloak derived from spatial analogue. (a) Block diagram and (b) waveform progression of temporal cloak. Roman numerals represent three key points in the link: I, after continuous-wave laser; II, after pulse generator and compressor; III, before digital communication analyzer. When the pulse generator and compressor are in operation the continuous-wave converted to a high-extinction, high-repetition rate chain of short pulse. Then it is obtained to the temporal gaps, wherein any events are cloaked.

converge and diverge in space-domain, a temporal cloak can be created through compressing and broadening the input light in time-domain by employing a pulse compressor and a time-domain Fraunhofer diffraction device. The block diagram of this cloak is illustrated in Fig. 1(a). After experiencing the pulse compressor, a CW is converted to a pulse train with some vacant time slots. Moreover, a large fractional hiding window might be created. In these long time gaps, any time events could not affect the probe beam and could not be detected by the digital communication analyzer (DCA). Subsequently, the ultrashort pulses with broadband spectrum propagates via the time-domain Fraunhofer device. Thus the waveform of pulse is broadened and resembles its spectrum after experiencing enough dispersion. Finally, the output waveform turns to be a continuous waveform, similar to the input waveform. Then the time gaps are completely closed. In order to exhibit the process of the cloak more clearly, the waveforms after CW laser, pulse generator and compressor, and time-domain Fraunhofer diffraction are shown in Fig. 1(b)I, II and III, respectively.

The experimental setup consists of three parts for temporal cloak, as shown in Fig. 2. The three parts are as follows: (1) a temporal gap generator (red dashed box), (2) a frequency-time mapping device (purple dashed box), and (3) a cloaked event emulator (blue dashed box). In the first part, a CW probe beam emitted by a tunable laser source (TLS), is injected into the temporal gap generator. The light propagates through a Mach-Zehnder modulator (MZM) and phase modulator (PM) synchronously driven by radio frequency (RF) signal. Afterwards, the CW can be cut and modulated to a common chirp pulse. Subsequently, the pulse is initially compressed by the first single mode fiber (SMF1), amplified by high power erbium-doped fiber amplifier (HP-EDFA), and injected into the HNLF, successively. Due to the self-phase modulation (SPM) effect in this HNLF, the pulse will be further compressed, indicating larger cloaking window. To obtain the shortest pulse width, the length of the second SMF (SMF2) is required to be optimized to properly compensate the chirp induced by SPM. The detailed principle of ultra-short-pulse generation can be referred in Ref. [21]. Thus, a large fractional cloaking window in a period is obtained. The second part is a frequency-time mapping device, which splices the gaps before DCA. The third SMF (SMF3) is used to act as a dispersive element to perform the frequency-to-time mapping. Finally, the third part contains an event emulator, which consisting of a dual drive Mach-Zehnder modulator (DMZM) driven by a dual radio frequency amplifier (DRFA) with bit pattern generator (BPG). In addition, all erbium-doped fiber amplifiers and polarization controllers are used to compensate the system loss and adjust polarization state for the communication link, respectively. It should be noted that the temporal gap generator and cloaked event emulator should keep synchronous.

In order to verify the cloak scheme, we numerically simulated the temporal cloak by solving the nonlinear Schrodinger equation. The key parameters used in the numerical simulation are listed as follows: the input wavelength is 1550 nm, the RF signal frequency is 10 GHz, the half-wave voltage of MZM is 5 V, the modulation depth of PM is 1.28π, the output power of HP-EDFA is 800 mW (cloak on), the dispersion slope of HNLF at 1550 nm is 0.03 ps/nm^2/km, the length of SMF1, HNLF, SMF2 and SMF3 are 7 km, 1.02 km, 0.4 km and 5 km, respectively. As shown in Fig. 3(a) and (b), a flat comb is obtained and the temporal gaps with the width of 91 ps are opened at the event plane. It should be noted that an effective time gap is defined as the width of the temporal waveform below the 10% of the peak-to-peak amplitude. The output waveforms of event and four cloak states are shown in Fig. 3(c) and (d). The event is simulated by 10 Gbit/s data with 33% dark return-to zero (RZ) modulation format and its eye diagram (black) is recorded. When the temporal cloak is turned off (namely, MZM and PM are turned off and the output power of HP-EDFA is turned down to 20 mW) and the event is turned on, a clear eye diagram (red) is obtained. Due to the dispersion of SMF3, there is slight broadening of the red eye diagram compared to the black eye diagram of event. Then, we turn on the cloak and hold the event on. A continuous waveform (green) is recorded, showing the event is hidden. As long as the event is turned off, whether cloak is turned on (pink) or off (blue), the output waveform is the same continuous waveform. The simulation results show that our solution is practicable to obtain a good temporal cloak.