Optical arbitrary waveform generator applicable to pulse generation and chromatic dispersion compensation of a remote UWB over fiber system

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Abstract: Optical arbitrary waveform generator (OAWG), which can generate pre-distorted ultra-wideband (UWB) pulses to tolerate the chromatic dispersion (CD) of the fiber without any other CD compensation solutions, provides a good solution for the UWB over fiber system. In our paper, we experimentally demonstrate a new OAWG scheme based on multiple incoherent continuous wave lights by double side band with suppressed carrier (DSB-SC) modulation. UWB Gaussian monocycle and doublet pulses are generated and the chromatic dispersion of 20-km, 50-km and 100-km single-mode fiber (SMF) are compensated by the OAWG system without any other CD compensation solutions.

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OCIS codes: (070.0070) Fourier optics and signal processing; (060.0060) Fiber optics and optical communications.

References and links

1. Introduction

Ultra-wideband (UWB) impulse radio, which is regulated by Federal Communications Commission (FCC) for indoor wireless communication operating in the frequency range from
3.1 to 10.6 GHz, has become a promising technology for wideband personal networks and sensor networks [1]. The typical communication distance of the UWB pulse is few meters to tens of meters because of the low power spectral density. The distance can be increased to several kilometers thanks to the UWB over fiber system, in which the UWB pulses are distributed to a remote site via fiber. The UWB over fiber technology provides an effective solution for high rate data access from anywhere [2]. However, due to the fiber chromatic dispersion (CD) impact, the UWB pulses of wide bandwidth can’t be transmitted further without any compensation. Furthermore, to distribute UWB signals over the fiber, it is highly desirable that the UWB signals can be generated in the optical domain directly [3,4].

Optical arbitrary waveform generator (OAWG), which can generate pre-distorted UWB pulses to tolerate the CD of the fiber without any other CD compensation solutions, provides a good solution for UWB over fiber system [5,6]. Many methodologies have been proposed for OAWG, among which line-by-line control according to Fourier transform theory has been widely adopted [7–11]. It generates arbitrary waveforms by independent manipulation of individual spectral lines, which can be achieved by diffraction gratings with a spatial light modulator [7–9], or high resolution arrayed-waveguide gratings with a modulator array [10,11].

In this paper, we propose and experimentally demonstrate a novel OAWG scheme based on multiple incoherent continuous wave (CW) lights employing double side band with suppressed carrier (DSB-SC) modulation. We control the intensity and phase of each electrical spectral line through manipulating every light wave and radio frequency (RF) signal without using high-resolution pulse shapers and coherent optical frequency comb, which are essential but complicated in the conventional line-by-line methods. Besides, the resolution of the previous systems is fixed when the setup completed, 10 GHz as common, but our system can resolve and control spectral lines with MHz to 10-GHz interval flexibly without change of the setup. In the experiment, we use four CW light sources to generate UWB Gaussian monocycle and doublet pulses, and compensate the CD of 20-km, 50-km, 100-km single-mode fiber (SMF) through waveform pre-distortion without any other CD compensation [12].

2. Experimental Setup and Principle

Figure 1 shows the proposed experimental setup. The wavelength of multiple incoherent CW lasers is \( \lambda_n \) \((n=1,2,3\cdots N)\), where \( N \) is the number of the lasers. The wavelength interval (\( \Delta \lambda \)) of the lights is tuned to wide enough to avoid interferences. Synchronized RF signals from four Signal Generators and DC bias are applied to Mach-Zehnder intensity modulators (MZM) to achieve double side band with suppressed carrier (DSB-SC) modulation on each CW light. The RF signals can be expressed as \( f_n(t) = A_n \cos(2\pi nf + \phi_n) \), \((n=1,2,3\cdots N)\), where \( A_n \) and \( \phi_n \) are corresponding amplitude and phase of the RF signal of number \( n \), and \( f \) is the fundamental frequency. An \( N \times 1 \) coupler combines the multiple modulated lights. Detected by a wideband photodiode (PD), the discrete electrical spectral lines are generated through beatings between each pair of optical spectral lines. The electrical field at the output of PD can be expressed as Eq. (1):

\[
E_{out}(t) = \sum_{n=1}^{N} J_1^{\beta_n}(\pi) I_n \exp(j(2\pi \times 2f_n t + 2\phi_n))
\]

where \( J_1(\bullet) \) is the 1st-order Bessel function of the first kind, \( \beta_n \) is modulation depth of DSB-SC, \( I_n \) is power of the laser and \( f_n = nf \). So the spectral interval and the phase of the electrical spectral lines are \( 2f \) and \( 2\phi_n \), respectively, and the radio frequency power are proportional to the power of CW lights.
In a remote UWB over fiber system, the UWB pulses are distributed to a remote site via fiber. Affected by the fiber attenuation and CD, the received signal $f_s(t)$ detected by PD is distorted as Eq. (2):

$$f_s(t) = L \sum_{n=1}^{N} F_n \alpha_n \exp\left[4\pi j(nft + \frac{2DF^2(n-1)}{c})\right]$$

where $L$ is the length of SMF, $F_n$ is Fourier series of the target signal, $\alpha_n$ is attenuation constant of SMF, $D$ is the dispersion coefficient and $c$ is the speed of light in vacuum.

Among Eq. (2), $\sum_{n=1}^{N} F_n \exp[2\pi j(n2ft)]$ is the target signal in the complex exponential form of Fourier series while $8\pi DF^2(n-1)2/c$ is the phase shift because of the CD. Physically, we can compensate the CD by imposing a spectral phase function equal and opposite to the phase shift due to CD [7]. Denote the transfer function of the dispersive fiber as $H_s(f)$. In order to pre-compensate the fiber dispersion, the required pre-compensate transfer function imposed on the target signals according to Eq. (2) should be given as Eq. (3):

$$H_s(f)^{-1} = A \sum_{n=1}^{N} \frac{1}{\alpha_n} \exp\left[-\frac{8\pi jDF^2(n-1)}{c}\right] \delta(f - 2f_n)$$

After pre-compensation, the received signal is proportional to the target signal, and $A$ is a scaling factor between them. The power loss will be compensated by an EDFA. So the required signal with pre-compensation is given by Eq. (4):

$$f_p(t) = F^{-1}(S(f) \times H_s(f)^{-1})$$

where $F^{-1}$ denotes the inverse Fourier transform and $S(f)$ is spectrum of the target signal. Hence we can obtain the values of $I_n$ and $\phi_n$ according to Eqs. (1) and (4), and the generated signals has a shape that is a scaled version of the user-designed shape.

It is important to choose appropriate $N$ according to the target signals. In our simulation, we choose 12-th UWB (the 12-th derivative of the Gaussian pulse) signal for the target signal and $L = 100$km. $N = 16$ is enough to generate the target signal. As Fig. 2(a) shows, the normalized magnitude spectrum (blue square) and phase spectrum (red asterisk) of the target signal are theoretical value, then the 12-th UWB signal is generated as seen in Fig. 2(b), which agree with the ideal signal. After transmission over 100-km SMF, the spectrum and
waveform of the received signal is distorted as shown in Figs. 2(c) and 2(d) respectively. Fiber loss is ignored in the simulation. To overcome the effect of the CD, additional phase shifts are imposed on each spectral line of the target waveform as shown in Figs. 2(e) and Fig. 2(f) shows the pre-distorted signal. Then after transmission, the spectrum and waveform of the received signal are closely resemble that of the target waveform as shown in Figs. 2(g) and 2(h) respectively.

Fig. 2. Simulation results: (b), (d), (f) and (h) are target waveform, received signal without pre-compensation, transmitted signal with pre-compensation and received signal with pre-compensation respectively. (a), (c), (e) and (g) are corresponding spectrum of (b), (d), (f) and (h) respectively (blue square: normalized magnitude spectrum of target signals; red asterisk: phase spectrum of target signals).
3. Experimental Results and Discussions

In the experiment, four CW lasers are used ($N = 4$) and their wavelengths are set to $\lambda_n = 1550nm + (n-1) \times \Delta \lambda$, $(n = 1, 2, 3, 4)$ and $\Delta \lambda$ is tuned to $2nm$ to avoid detectable interferences with a 70-GHz photodiode. Synchronized RF signals and DC bias are applied to Mach-Zehnder intensity modulators to achieve DSB-SC modulation on each CW light, and the power of the sidebands is at least 15dB higher than power of the carrier. By optimally adjusting the power of the CW lights and the phase of the RF signals, arbitrary waveforms including UWB Gaussian monocycle and doublet pulses can be generated. For UWB generation, the fundamental frequency $f$ is set to 1.25 GHz. Figures 3(a)-3(d) show the waveform and spectrum of the generated monocycle and doublet pulses respectively. The blue solid lines of Figs. 3(a) and 3(c) show the generated waveforms while the red dashed lines show the target waveforms. Obviously, the generated and target waveforms are very close with a negligible deviation. The cross correlation coefficients (CCCs) between them are 0.9252 and 0.9501 respectively. As seen from Figs. 3(a) and 3(b), full-width at half-maximum (FWHM) and 10-dB bandwidth of the monocycle pulses are 49.4ps and 5GHz respectively. The counterpart of the doublet in Figs. 3(c) and 3(d) is 47ps and 5GHz respectively. The spectra of the monocycle and doublet pulses are measured by a RF spectrum analyzer (Agilent E4446A) and both fit the FCC mask. All the waveforms are measured with an 80-GHz sampling oscilloscope (Agilent 86100C).

![Fig. 3.](image)

Fig. 3. (a) and (c) are generated monocycle and doublet pulse respectively (blue and solid line: generated waveform; red and dashed line: target waveform); (b) and (d) are corresponding spectrum of (a) and (c) respectively.

The CD compensation capability of the OAWG system is tested by receiving pre-distorted monocycle and doublet pulses after transmission. Without pre-compensation, the monocycle and doublet pulses are distorted seriously after transmission over 20-km, 50-km, 100-km SMF shown by the red lines of (a), (b), (c) in Fig. 4 and Fig. 5, respectively. To overcome the effect of the CD, additional phase shifts are imposed on each spectral line to compensate the group delay differences between them. Figures 4(d)-4(f) and Figs. 5(d)-5(f) show the pre-distorted monocycle and doublet pulses prior to transmission respectively. The blue lines of Figs. 4(a)-4(c) and Figs. 5(a)-5(c) show the received monocycle and doublet pulses with pre-
compensation after propagating through 20-km, 50-km and 100-km SMF respectively, which closely resemble the origin waveform (black lines in Fig. 4 and Fig. 5). Figures 6(a)-6(c) and Figs. 7(a)-7(c) show the spectrum of the origin waveforms and the received waveforms with pre-compensation of Figs. 4(a)-4(c) and Figs. 5(a)-5(c) respectively. The amplitude spectrum of the origin waveforms (blue square) and the received waveforms (blue diamond) are almost the same. So are they for the phase spectrum of the origin waveforms (red circle) and the received waveforms (red cross).

Fig. 4. Monocycle: (a), (b) and (c) are received signals after transmission over 20-km, 50-km 100-km SMF respectively (black: origin signal; blue: received signals with pre-compensation; red: received signals without pre-compensation); (d), (e) and (f) are transmitted signals with pre-compensation before transmission over 20-km, 50-km 100-km SMF respectively.

Fig. 5. Doublet: (a), (b) and (c) are received signals after transmission over 20-km, 50-km 100-km SMF respectively (black: origin signal; blue: received signals with pre-compensation; red: received signals without pre-compensation); (d), (e) and (f) are transmitted signals with pre-compensation before transmission over 20-km, 50-km 100-km SMF respectively.
Fig. 6. Monocycle: (a), (b) and (c) spectrum of target signals and received signals with pre-compensation after transmission over 20-km, 50-km 100-km SMF respectively. (blue and square: normalized magnitude spectrum of target signals; blue and diamond: normalized magnitude spectrum of received signals; red and circle: phase spectrum of target signals; red and cross: phase spectrum of received signals).

Fig. 7. Doublet: (a), (b) and (c) spectrum of target signals and received signals with pre-compensation after transmission over 20-km, 50-km 100-km SMF respectively. (blue and square: normalized magnitude spectrum of target signals; blue and diamond: normalized magnitude spectrum of received signals; red and circle: phase spectrum of target signals; red and cross: phase spectrum of received signals).

It is true that the deviations between targeted and obtained results do exist. Though we obtained the optimal operating conditions according to Eq. (1) and Eq. (4) in the paper, the conditions are too difficult to be achieved. In the experiment, we compensated the chromatic dispersion of the fiber manually, the experimental error caused the non-perfect compensation mostly in our opinion. Figures 8(a) and 8(b) show the CCCs between the received monocycle/doublet signals and the origin waveforms respectively. The results with pre-compensation are close to 1, which proves that the CD are almost compensated completely by the OAWG pre-distortion without any other CD compensation solutions.

Unlike other OAWG systems, our system can flexibly resolve and control spectral lines with an interval from MHz to 10GHz without change of setup while the resolution of the
previous systems is fixed when the setup completed. In other words, our OAWG system can generate the signals which the existing electrical arbitrary waveform generator (EAWG) can and cannot generate. Moreover, our system is simple and stable without the use of high resolution pulse shapers and coherent optical frequency comb. Of course, more RF signals should be used for generating more complicated and precise waveforms, which makes the system also complicated and costly. Simplifying and integrating the system will be our next work.

4. Conclusions

We experimentally demonstrate a novel OAWG scheme based on multiple incoherent CW lights with DSB-SC modulation. Based on the OAWG system, the UWB Gaussian monocycle and doublet pulses are generated with the spectrum fitting to FCC mask. Through the use of pre-distortion in the UWB generation, the received signals after transmission over 20-km, 50-km and 100-km SMF are closely resemble to the origin waveform without any other CD compensation solutions. It proves the capability of the CD compensation provided by the OAWG, which could improve the bit error rate performance in a practical UWB over fiber system.

Acknowledgments

This work was supported in part by National Basic Research Program of China under the grant No 2012CB315603 and 2012CB315604, National Nature Science Foundation of China (NSFC) under grant No. 60736003, 61025004, 61032005.