Optical ultra-wideband pulse generation and distribution using a dual-electrode Mach-Zehnder modulator

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A novel approach to generate and distribute ultra-wideband (UWB) pulses in optical domain is investigated. In this proposed scheme, a dual-electrode Mach-Zehnder modulator (DE-MZM) is biased at its quadrature point so as to realize the linear response. Then the intensity of output optical field can be assumed to the subtraction of two input Gaussian pulses. If the input Gaussian pulses are with the same sharp parameters but different time delays, a quasi-monocycle-waveform UWB signal can be generated. If the input Gaussian pulses are with different amplitudes and full-width at half-maximum (FWHM), a quasi-doublet-waveform UWB signal can be generated. A transmission of the UWB signals through a 25-km single mode fiber is carried out successfully. The results in both temporal and frequency domains are also presented.

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Ultra-wideband (UWB) systems have attracted a lot of attention in recent years. Their abilities of delivering high bit rate data, good wall penetration, low power consumption, multi-path, and interference immunity make them very promising solutions to many communication problems, such as consumer indoor wireless communications, medical and military communicatios, etc. In 2002, the US Federal Communications Commission (FCC) approved the unlicensed use of the UWB spectrum from 3.1 to 10.6 GHz for indoor communications, with a power spectral density (PSD) lower than –41.3 dBm/MHz. Based on the FCC definition, an UWB signal should have a spectral bandwidth greater than 500 MHz or a fractional bandwidth greater than 20%[1,2]. Since the PSD of UWB signals is limited, the propagation of UWB signal is limited to several meters. The technology of UWB-over-fiber can solve the problem by connecting the Center Station (CS) and Base Station BS with optical fiber, taking the advantage of low loss, wideband, and immunity to electromagnetic interference offered by optical fibers. Another significant advantage of the optical domain is that it can provide broadband all-optical signal processing.

The choice of the UWB pulse shapes is critical to the performance of the UWB system. Gaussian monocycle and doublet pulses have been considered as promising candidates for UWB communications[3]. There are two different ways to generate UWB signal, one is electrical scheme[4,5] and the other is optical scheme[6−11]. It is desirable that the UWB signals can be generated directly in the optical domain to avoid the costly electrical to optical conversion. Several methods have been proposed to generate and distribute Gaussian monocycle and doublet pulses, including the generation of the UWB pulses using a frequency-shift-keying modulator[7], a nonlinearly biased Mach-Zehnder modulator[8], a two-tap microwave delay-line filter with coefficients of $(1-1)$[9], or an optical spectrum shaper with frequency-to-time mapping[10,11].

In this letter, a novel approach to generating and distributing UWB pulses in optical domain is carried out and proved. In the proposed system the bias voltages of dual-electrode Mach-Zehnder modulator (DE-MZM) are $V_{\text{bias-up}} = 0$ and $V_{\text{bias-down}} = V_\pi/2$. Thus a DE-MZM is biased at its quadrature point, and then the DE-MZM is operated at the linear region of its transfer function. The intensity of the output optical field can be assumed to the subtraction of two input Gaussian pulses. If the two Gaussian pulses are with different time delays, a Gaussian quasi-monocycle pulse can be generated; if the two Gaussian pulses are with different amplitudes and full-width at half-maximum (FWHM), a Gaussian quasi-doublet pulse can be generated. By adjusting the parameters of system, an UWB quasi-monocycle or quasi-doublet pulse is obtained at the output of a photodiode (PD). The transmission of the UWB signals through a 25-km single mode fiber (SMF) is carried out successfully. Vertification based on the proposed approach are carried out and the results in both temporal and frequency domains are presented.

With a DE-MZM biased at quadrature point, Fig. 1 shows a conceptual diagram of the generation and distribution of UWB monocycle pulse and UWB doublet pulse. As can be seen from Fig. 1, the optical field at the input of the DE-MZM can be written as

$$E_{\text{in}} = E_{\text{c}}\exp\left[\mathrm{j}\omega_{\text{c}}t + \mathrm{j}\phi\left(t\right)\right], \qquad (1)$$

where E_{c} denotes the amplitude of the optical field, ω_{c} represents the angular frequency of the optical carrier, and $\phi\left(t\right)$ is the phase noise of the laser diode. The DE-MZM is biased at its quadrature point. The electrical driving signals sent into two arms of DE-MZM are the Gaussian pulses $g_1(t)$ and $g_2(t)$. Moreover, the bias voltages of DE-MZM are $V_{\text{bias-up}} = 0$ and $V_{\text{bias-down}} = V_\pi/2$. Thus the DE-MZM is operated at the linear region of its transfer function. The optical field at the output

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of the DE-MZM can be expressed as

$$E(t) = E_{\text{in}}(t)\exp\left[\mathrm{j}\pi \times \frac{g_1(t)}{V_\pi}\right] + E_{\text{in}}(t)\exp\left[\mathrm{j}\pi \times \frac{g_2(t)}{V_\pi} + \mathrm{j}\frac{\pi}{2}\right], \qquad (2)$$

where V_π denotes the half-wave voltage of the MZM. Following the square-law detection using a PD with responsivity R, the photocurrent can be expressed as

$$i(t) = \frac{1}{2}RE(t)E^*(t) = RE_{\text{c}}^2\left\{1 + \sin\left[\frac{\pi}{V_\pi}(g_1(t) - g_2(t))\right]\right\}. \qquad (3)$$

As can be seen in Eq. (3), the phase modulation signals with shapes of $g_1(t)$ and $g_2(t)$ are converted to the intensity modulation signals with the shape of $\sin\left[\frac{\pi}{V_\pi}(g_1(t) - g_2(t))\right]$, which can be assumed to the subtraction of $g_1(t)$ and $g_2(t)$. In order to generate Gaussian quasi-monocycle pulse, the electrical driving signals sent into two arms of DE-MZM are $g_1(t) = A_{\text{p}}e^{-\frac{1}{2}\left(\frac{t}{T_{\text{FWHM}}}\right)^{2N}}$ and $g_2(t) = A_{\text{p}}e^{-\frac{1}{2}\left(\frac{t-\tau}{T_{\text{FWHM}}}\right)^{2N}}$, respectively. Where A_{p} represents the parameter of peak-to-peak amplitude, T_{FWHM} is the time of full-wave at half-maximum, N is the order of the Gaussian pulse with the default value of $N = 1$, and τ is the time delay coefficient. Thus the Gaussian pulses $g_1(t)$ and $g_2(t)$ are with the same shape parameter but different time delays, which is realized by setting the time delay parameter of electrical time delay line (Fig. 1(a)). The intensity of optical field is a quasi-monocycle-waveform pulse (Fig. 2(a)).

In order to generate Gaussian quasi-doublet pulse, the electrical driving signals sent into two arms of DE-MZM are $g_1(t) = A_{\text{p1}}e^{-\frac{1}{2}\left(\frac{t}{T_{\text{FWHM1}}}\right)^{2N}}$ and $g_2(t) = A_{\text{p2}}e^{-\frac{1}{2}\left(\frac{t}{T_{\text{FWHM2}}}\right)^{2N}}$, respectively. Where A_{p1} and A_{p2} represent the parameters of peak-to-peak amplitude of Gaussian pulses, T_{FWHM1} and T_{FWHM2} are the time of FWHM of Gaussian pulses, and N is the order of the Gaussian pulse with default value of $N = 1$. Thus the Gaussian pulses $g_1(t)$ and $g_2(t)$ are with different amplitudes and FWHMs, which are realized by

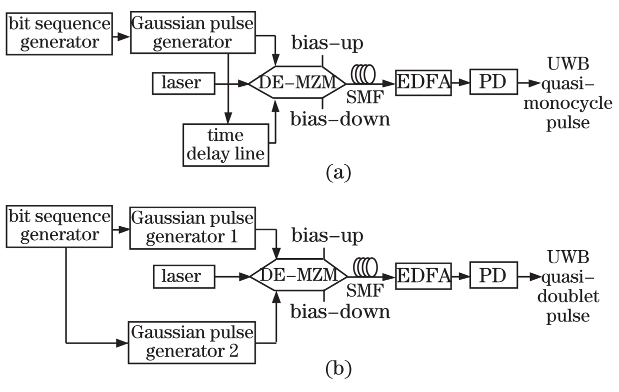

Fig. 1. Block diagram of (a) Gaussian quasi-monocycle and (b) quasi-doublet pulse generation and transmission system.

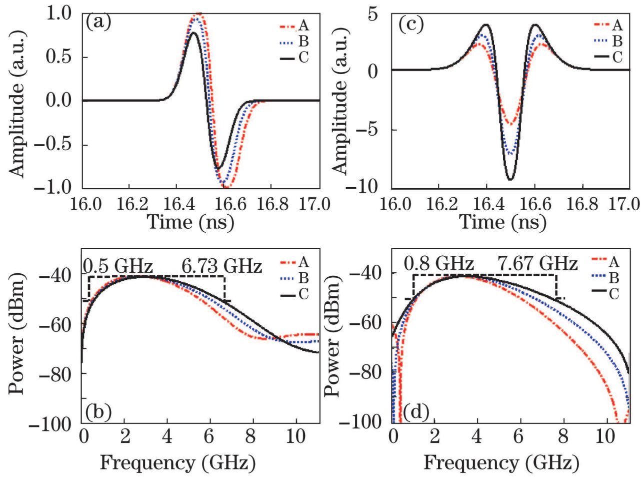

Fig. 2. Schematic (a) pulse waveform and (b) radio frequency spectrum of UWB Gaussian quasi-monocycle pulse; schematic (c) pulse wavefrom and (d) radio frequency spectrum of UWB Gaussian quasi-doublet pulse.

Table 1. Generation of Gaussian Quasi-monocycle Pulse (in Figs. 2(a) and (b))

	A	B	C
A_{p} (a.u.)	1	1	1
T_{FWHM} (ps)	50	50	50
τ (ps)	100	75	50
–10-dB Bandwidth (GHz)	5.41	5.79	6.23
Fractional Bandwidth	180%	176%	172%

setting the parameters of Gaussian pulse generator (Fig. 1(b)). The intensity of optical field is a quasi-doublet-waveform pulse (Fig. 2(c)).

The generation of Gaussian quasi-monocycle and quasi-doublet pulse can be simulated by using Matlab. In the program, the parameters of Gaussian pulse can be set as Table 1 shows. Gaussian quasi-monocycle pulses are obtained, as shown in Figs. 2(a) and (b), by adjusting the coefficient of the electrical time delay line. The –10-dB bandwidth of quasi-monocycle pulses is related to the time delay coefficient. As τ decreases, the –10-dB bandwidth in spectrum will be broaden. When τ equals 50 ps, the –10-dB bandwidth is 6.23 GHz (from 0.5 to 6.73 GHz) and the fractional bandwidth is 172%.

Gaussian quasi-doublet pulses are obtained, as shown in Figs. 2(c) and (d), by adjusting the parameter of Gaussian pulse (Table 2). The –10-dB bandwidth of quasi-doublet pulses is related not only to the difference of pulse amplitude between the two Gaussian pulses, but also to the difference of FWHM. When $A_{\text{p2}} = 2.8$, $A_{\text{p1}} = 1.4$ a.u., and $T_{\text{FWHM2}} = 0.4$, $T_{\text{FWHM1}} = 40$ ps are satisfied, the – 10-dB bandwidth is 6.87 GHz (from 0.8 to 7.67 GHz) and the fractional bandwidth is 162%.

Because the dispersion fiber is used as transmission media, the amplitude of output signal must satisfied the nonlinear Schrodinger equation as

$$\mathrm{j}\frac{\partial A}{\partial z} + \frac{\mathrm{j}\alpha}{2}A - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + \gamma|A|^2 A = 0, \qquad (4)$$

Table 2. Generation of Gaussian Quasi-Doublet Pulse (in Figs. 2(c) and (d))

	A	B	C
A_{p1}	0.5	0.5	0.5
A_{p2}	0.8	1	1.4
T_{FWHM1} (ps)	100	100	100
T_{FWHM2} (ps)	60	50	40
–10-dB Bandwidth (GHz)	5.44	6.28	6.87
Fractional Bandwidth	146%	153%	162%

where α is the fiber loss index, β_2 is dispersion parameter of fiber, and γ is the nonlinear index. When the loss and nonlinear effect can be neglected, Eq. (4) becomes

$$\mathrm{j}\frac{\partial A}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2}. \quad (5)$$

According to Eq. (2), at the output of DE-MZM, the optical UWB signal can be expressed as

$$A(z=0,t) = \sqrt{\frac{1}{2}E(t)E^*(t)} = \sqrt{2}E_c \sin\left[\frac{\pi}{2V_\pi}(g_1(t) - g_2(t)) + \frac{\pi}{4}\right]. \quad (6)$$

Expanding Eq. (4) with Taylor series as

$$\begin{aligned} A(z=0,t) &= \sqrt{2}E_c\left\{a_0 + a_1\cdot\left[\frac{\pi}{2V_\pi}(g_1(t)-g_2(t))+\frac{\pi}{4}\right]\right. \\ &+ a_2\cdot\left[\frac{\pi}{2V_\pi}(g_1(t)-g_2(t))+\frac{\pi}{4}\right]^2 \\ &+ a_3\cdot\left[\frac{\pi}{2V_\pi}(g_1(t)-g_2(t))+\frac{\pi}{4}\right]^3\cdots \\ &\left.+ a_n\cdot\left[\frac{\pi}{2V_\pi}(g_1(t)-g_2(t))+\frac{\pi}{4}\right]^n+\cdots\right\}, \quad (7)\end{aligned}$$

where $a_0 = 0$, $a_1 = 1$, $a_2 = 0$, $a_3 = -\frac{1}{3!}$, $\cdots$, $a_{2k} = 0$, and $a_{2k-1} = (-1)^{k-1}\frac{1}{(2k-1)!}$. Because a_1, a_3, and a_5 are 1, –1/6, and 1/120, without causing significant error, the equations can be further simplified if the a_3 and a_5 terms are dropped. The optical UWB signal can be assumed to

$$A(z=0,t) \approx \sqrt{2}E_c\cdot\left[\frac{\pi}{2V_\pi}(g_1(t)-g_2(t))+\frac{\pi}{4}\right]. \quad (8)$$

According to Eq. (5), if $A(z=0,t)$ is Gaussian quasi-monocycle pulse, the amplitude of the optical UWB signal after propagating through a fiber with a length of L is given by

$$\begin{aligned} A(z=L,t) &= \frac{E_c\pi}{2\sqrt{2}} + \frac{\pi E_c}{\sqrt{2}V_\pi}\frac{A_p}{(1-\mathrm{i}L/L_D)^{1/2}} \\ &\times\left\{\exp\left[-\frac{(t/T_{FWHM})^2}{2(1-\mathrm{i}L/L_D)}\right]\right. \\ &\left.-\exp\left[-\frac{((t-\tau)/T_{FWHM})^2}{2(1-\mathrm{i}L/L_D)}\right]\right\}, \quad (9)\end{aligned}$$

where $L_D = \frac{T_{FWHM}^2}{|\beta_2|}$ is the dispersion length. Figure 3 (a) shows the intensity of UWB quasi-monocycle signal corresponding to fiber length when $E_c^2 = 10$ mW, $V_\pi = 4$, $T_{FWHM} = 50$ ps, $A_p = 1$ a.u., $\tau = 50$ ps, and $\beta_2 = 16$ ps/(nm·km).

According to Eq. (5), if $A(z=0,t)$ is Gaussian quasi-doublet pulse, the amplitude of the optical UWB signal after propagating through a fiber with a length L is given by

$$\begin{aligned} A(z=L,t) &= \frac{E_c\pi}{2\sqrt{2}} + \frac{\pi E_c}{\sqrt{2}V_\pi} \\ &\times\left\{\frac{A_{p1}}{(1-\mathrm{i}L/L_{D1})^{1/2}}\exp\left[-\frac{(t/T_{FWHM1})^2}{2(1-\mathrm{i}L/L_{D1})}\right]\right. \\ &\left.-\frac{A_{p2}}{(1-\mathrm{i}L/L_{D2})^{1/2}}\exp\left[-\frac{(t/T_{FWHM2})^2}{2(1-\mathrm{i}L/L_{D2})}\right]\right\}, \quad (10)\end{aligned}$$

where $L_{D1} = \frac{T_{FWHM1}^2}{|\beta_2|}$ and $L_{D2} = \frac{T_{FWHM2}^2}{|\beta_2|}$. Figure 3(b) shows the intensity of UWB quasi-doublet signal corresponding to fiber length when $E_c^2 = 10$ mW, $T_{FWHM1} = 100$ ps, $A_{p1} = 0.5$ a.u., $T_{FWHM2} = 40$ ps, $A_{p2} = 1.4$ a.u., $V_\pi = 4$, and $\beta_2 = 16$ ps/(nm·km).

As can be seen in Figs. 3(a) and (b), after propagating through 25-km SMF, the chromatic dispersion induced by fiber cannot affect the UWB pulse much.

To verify the proposed method, vertifications are conducted using a commercial software. A laser with an output power of 15 dBm is used to generate the incident light-wave. The user defined bit sequence generator generates a bit sequence at a bit rate of 5 Gbps with a fixed pattern (one "1" per 16 bits), which is equivalent to a Gaussian pulse train with a repetition rate of 0.3125 GHz. The parameters of DE-MZM are set at $V_\pi = 4$ V, $V_{bias-up} = 0$ V, and $V_{bias-down} = 2$ V.

In order to generate UWB Gaussian quasi-monocycle pulse, the parameters of Gaussian pulse generator in Fig. 1(a) are set at $A_p = 1$ a.u. and $T_{FWHM} = 50$ ps. The time delay coefficient τ is set to be 50 ps. When a 25-km single mode fiber (fiber dispersion parameter 16 ps/(nm·km) is used, the quasi-monocycle pulse with pulse duration of 317 ps can be obtained. Figures 4(a) and (b) show the temporal and spectral results measured. The temporal interference and the spectral width drops after fiber transmission are so small that they can be neglected. The envelope of the discrete

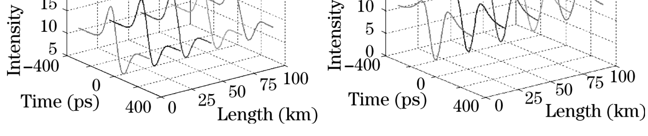

Fig. 3. Gaussian (a) qusi-monocycle and (b) quasi-doublet waveform corresponding to fiber length.

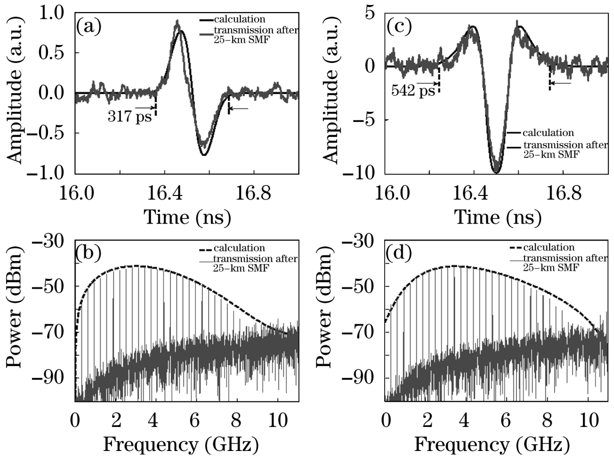

Fig. 4. Results of (a) waveform and (b) radio frequency spectrum of UWB Gaussian quasi-monocycle pulse; (c) waveform and (d) radio frequency spectrum of UWB Gaussian quasi-doublet pulse after 25-km SMF transmissions.

spectrum corresponding to the spectrum of a quasi-monocycle pulse agrees well with the calculation results, which has a center frequency of about 3.36 GHz and a – 10-dB bandwidth of 6.23 GHz (from 0.5 to 6.73 GHz), indicating that the fractional bandwidth is 172%.

In order to generate UWB Gaussian quasi-doublet pulse, the parameters of Gaussian pulse generator in Fig. 1(b) are set at $A_{p1} = 0.5$ a.u. and $A_{p2} = 1.4$ a.u., $T_{FWHM1} = 100$ ps and $T_{FWHM2} = 40$ ps. The waveform and radio frequency spectrum of UWB pulse after 25-km single mode fiber transmission is shown in Figs. 4(c) and (d), respectively. Figure 4(c) shows the waveform of the generated quasi-doublet pulses with pulse duration of 542 ps. The degradation in the UWB waveform and spectrum due to fiber transmission can also be eliminated. It is can be seen in Fig. 4(d) that the envelope of the discrete spectrum corresponding to the spectrum of a quasi-doublet pulse agrees well with the calculation results, which has a center frequency of about 3.87 GHz and a – 10-dB bandwidth of 6.87 GHz (from 0.8 to 7.67 GHz), indicating that the fractional bandwidth is 162%.

In conclusion, We have proposed a novel approach to generate and distribute optical UWB pulses using the DE-MZM biased at its quadrature point. Thus the DE-MZM is operated at the linear region of its transfer function. Then the intensity of output optical field can be assumed to the subtraction of two input Gaussian pulses. By adjusting the parameter of input Gaussian pulses used to drive the DE-MZM, a Gaussian quasi-monocycle UWB pulse with a center frequency of about 3.36 GHz and a – 10-dB bandwidth of 6.23 GHz, a Gaussian quasi-doublet UWB pulse with a center frequency of about 3.87 GHz and a −10-dB bandwidth of 6.87 GHz, are generated experimentally and distributed by 25-km SMF. The experimental results measured in both temporal and frequency domains agree well with the calculated result. Although the Gaussian quasi-monocycle and quasi-doublet pulsed do not efficiently exploit the spectral mask imposed by FCC, they can be useful for less power-critical application.

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