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<td><strong>Citation</strong></td>
<td>Huang, T., Fu, S., Li, J., Chen, L. R., Tang, M., Shum, P., &amp; Liu, D. (2013). Reconfigurable UWB pulse generator based on pulse shaping in a nonlinear optical loop mirror and differential detection. Optics Express, 21(5), 6401-6408.</td>
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<td><strong>Date</strong></td>
<td>2013</td>
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Reconfigurable UWB pulse generator based on pulse shaping in a nonlinear optical loop mirror and differential detection

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Abstract: A reconfigurable impulse radio ultra-wideband (UWB) pulse generator for various UWB shapes (e.g., monocycle, doublet, and triplet pulses) based on a nonlinear optical loop mirror (NOLM) and differential detection is proposed and experimentally demonstrated. The proposed approach can be used with different modulation formats and may be suitable for implementation in future low-cost, high-speed, short-range UWB wireless access applications.

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OCIS codes: (999.9999) Microwave photonics; (999.9999) Ultra-wideband; (070.4340) Nonlinear optical signal processing; (060.2330) Fiber optics communications.

References and links

Ultra-wideband (UWB) impulse radio technology has attracted considerable interest for its applications in short-range, high-throughput, and high capacity wireless personal area networks and sensor networks, due to advantages such as low cost, immunity to multi-path fading, and feasibility of sharing bandwidth with existing wireless systems [1]. In 2002, the US Federal Communications Commission (FCC) approved the unlicensed use of the UWB spectrum from 3.1 to 10.6 GHz with a power spectral density (PSD) lower than $-41.3 \text{ dBm/MHz}$. Based on these FCC regulations, a UWB signal must have a spectral bandwidth greater than 500 MHz or a fractional bandwidth greater than 20% [2]. Until now, existing techniques of impulse radio UWB pulse generation can be classified into two approaches: electric and photonic. While it is possible to generate Gaussian pulses directly in the electrical domain, it is more challenging to obtain more complex UWB waveforms such as monocycle, doublet, and triplet pulses. As such, there has been considerable effort in developing photonic approaches for UWB pulse generation. Photonic approaches also have the advantages of supporting wide bandwidth and being tunable, reconfigurable, as well as compatible with fiber-optic transmission. Various photonic approaches have been proposed to generate UWB pulses, using cross gain and cross

1. Introduction

Ultra-wideband (UWB) impulse radio technology has attracted considerable interest for its applications in short-range, high-throughput, and high capacity wireless personal area networks and sensor networks, due to advantages such as low cost, immunity to multi-path fading, and feasibility of sharing bandwidth with existing wireless systems [1]. In 2002, the US Federal Communications Commission (FCC) approved the unlicensed use of the UWB spectrum from 3.1 to 10.6 GHz with a power spectral density (PSD) lower than $-41.3 \text{ dBm/MHz}$. Based on these FCC regulations, a UWB signal must have a spectral bandwidth greater than 500 MHz or a fractional bandwidth greater than 20% [2]. Until now, existing techniques of impulse radio UWB pulse generation can be classified into two approaches: electric and photonic. While it is possible to generate Gaussian pulses directly in the electrical domain, it is more challenging to obtain more complex UWB waveforms such as monocycle, doublet, and triplet pulses. As such, there has been considerable effort in developing photonic approaches for UWB pulse generation. Photonic approaches also have the advantages of supporting wide bandwidth and being tunable, reconfigurable, as well as compatible with fiber-optic transmission. Various photonic approaches have been proposed to generate UWB pulses, using cross gain and cross
phase modulation (XGM/XPM) in a semiconductor optical amplifier (SOA) [3–5];
frequency-to-time mapping [6–9]; phase-to-intensity (PM-IM) modulation conversion
[10–13]; microwave photonic delay line filters [14–16]; direct current modulation of
semiconductor lasers [17, 18]; sum-frequency generation in periodically poled lithium niobate
waveguides [19]; the nonlinear transmission region of an electro-optic modulator [20]; and
various effects in highly nonlinear fiber (HNLF) such as pulse shaping with a nonlinear optical
loop mirror (NOLM) [21], nonlinear polarization rotation [22], four-wave mixing (FWM) [23],
and parametric amplification [24]. However, without proper power attenuation, the frequency
spectra of the UWB pulses generated by most existing methods may not fully satisfy the FCC
spectral mask. As a result, the UWB signals may be too weak so that the wireless transmission
distance is limited. Besides the FCC-specific spectral mask, it is also desirable for the UWB
pulse generators to be reconfigurable so that different modulation formats such as on-off
keying (OOK), pulse shape modulation (PSM), bi-phase modulation (BPM), and pulse position
modulation (PPM) can be used. Several switchable UWB pulse generators have been reported
in [5–7, 9–12, 14–16, 23]. For example, a UWB pulse generator based on pulse shaping and
fiber Bragg gratings (FBGs) has been demonstrated in [9]. However, such an all-fiber
implementation requires mode-locked fiber lasers and specially designed spectral-shaping
components. Bolea et al. reported a reconfigurable UWB pulse generator which can be applied
to different pulse modulation formats using an \(N\) tap microwave photonic filter [16]. In
principle, such a scheme can be used to produce any higher-order UWB pulse, but the number
of lasers required increases with the number of filter taps, e.g., in order to generate triple
pulses, 4 lasers with equal wavelength spacing are needed. Li et al. presented an approach for
generating UWB triplet pulses by employing four-wave mixing (FWM) and PM-IM
conversion [23]. The major restriction with this approach is that the UWB pulse generated at
the idler wavelength may suffer from low signal-to-noise ratio (SNR) due to low FWM
efficiency.

In this paper, we propose and experimentally demonstrate a reconfigurable UWB pulse
generator to produce UWB monocycle, doublet, and triplet pulses with inverted polarity. The
operation principle lies in the ability to shape pulses using the different transfer functions of a
NOLM by adjusting the state of polarization (SOP) of the pump and probe signals. The NOLM
output can be further shaped to produce monocycle or triplet pulses after differential detection.
In addition, various modulation formats including OOK, PSM, BPM, and PPM can take
advantage of our proposed UWB pulse generator.

**2. Operation principle and experiment setup**

We use a NOLM for pulse shaping as shown in Fig. 1(a). Generally, the NOLM incorporates a
section of highly nonlinear fiber (HNLF), a polarization controller (PC), two WDM couplers,
and a 3-dB coupler. The probe and pump signals are launched into the NOLM through the 3-dB
coupler and WDM coupler 1, respectively. WDM coupler 2 is used to couple out the pump. The
probe is split into the clockwise (CW) and counter-clockwise (CCW) components as follows:

\[
E_{cw} = \frac{\sqrt{2}}{2} E_{in} = \frac{\sqrt{2}}{2} (E_{in}^x + E_{in}^y)
\]

\[
E_{ccw} = \frac{\sqrt{2}}{2} E_{in} e^{i \phi} = \frac{\sqrt{2}}{2} (E_{in}^x + E_{in}^y) e^{i \phi}
\]

where, \(E_{in}^x\) and \(E_{in}^y\) are the x and y polarization components of the input probe signal \(E_{in}\).
When a pump $E_p$ is launched into the NOLM, both the CW and CCW light will experience a nonlinear phase shift due to XPM in the HNLF. The nonlinear phase shift experienced by the CW probe is determined by the instantaneous optical power of the pump, while the nonlinear phase shift experienced by the CCW probe is determined by the average optical power of the pump. If the duty cycle of the pump pulse is very small, the nonlinear phase shift of the CCW probe is much smaller than that of the CW probe. As a result, the corresponding nonlinear phase shift can be neglected. Moreover, the nonlinear phase shift induced by self-phase modulation (SPM) on the probe can also be neglected owing to the relatively weak probe power. The nonlinear phase shift of the CW probe induced via XPM depends on the SOP of both the pump and probe. As such, the PC is an essential component and its role in determining the NOLM transfer function can be described by the product of two matrices [25]:

$$M_1 = \begin{pmatrix} 1 & 0 \\ 0 & e^{-i\phi} \end{pmatrix}, \quad M_2 = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}$$ (3)

where $\phi$ is the static phase shift between the two orthogonal SOPs induced by the PC and $\theta$ presents a polarization rotation effect. The electric fields of the output probe from the NOLM, $E_{cw}^{out}$ and $E_{ccw}^{out}$, can be expressed as:

$$E_{cw}^{out} = \frac{1}{\sqrt{2}} (M_2 M_1) \begin{pmatrix} e^{i\phi_{cw}} \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} E_{in}^{x} \cos \theta e^{i\phi_{in}} - E_{in}^{y} \sin \theta e^{i(\phi_{in} - \phi)} \\ E_{in}^{x} \sin \theta e^{i\phi_{in}} + E_{in}^{y} \cos \theta e^{i(\phi_{in} - \phi)} \end{pmatrix}$$ (4)

$$E_{ccw}^{out} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \end{pmatrix} (M_1 M_2) \begin{pmatrix} E_{in}^{x} \\ E_{in}^{y} \end{pmatrix} e^{i\phi} = -\frac{1}{\sqrt{2}} \begin{pmatrix} E_{in}^{x} \cos \theta - E_{in}^{y} \sin \theta \\ E_{in}^{y} \sin \theta e^{-i\phi} + E_{in}^{x} \cos \theta e^{-i\phi} \end{pmatrix}$$ (5)

where, $\phi_{cw}^{x}$ and $\phi_{cw}^{y}$ are the nonlinear phase shifts of the CW signals along the two orthogonal polarization axes. After interference in the 3-dB coupler, the output power $P_{out}$ of the NOLM is:

$$P_{out} = \frac{\sqrt{2}}{2} (E_{cw}^{out} + E_{ccw}^{out})^2$$ (6)

The NOLM output is determined by many parameters including the SOPs of the pump and probe, pump power, phase shift $\phi$, and polarization rotation $\theta$. In particular, if the SOP of the pump and probe are set to be parallel and if $\theta = \pi/2$, the NOLM transfer function will change for different values of $\phi$, which are controlled by the PC. For example, when $\phi = \pi$, we obtain the conventional transmission curve of the NOLM, as shown in Fig. 1(b). This is the well-known...
transfer function which is often exploited for wavelength conversion applications (e.g., a pump pulse with a Gaussian profile can be transferred to the probe wavelength). On the other hand, for $\varphi$ set to different values, the NOLM transfer function can be used to generate UWB doublet pulses, as shown in Figs. 1(b) and 1(c), i.e., varying $\varphi$ allows us to set the operating bias point of the transfer function. As a result, for a Gaussian pump pulse with a fixed power, the NOLM output can be switched between a Gaussian and a doublet pulse by properly setting the PC.

It is well known that a monocycle pulse can be obtained by differentiating a Gaussian pulse; this first-order derivative can be approximated by a first-order difference realized using a 2-tap microwave delay line filter with tap coefficients $(1, -1)$. Accordingly, a triplet pulse can be obtained by differentiating a doublet pulse, or equivalently by implementing a first-order difference to the doublet pulse [14]. We use an optical tunable delay line (OTDL) and a balanced photodetector (PD) to function as a 2-tap microwave delay line filter for the purpose of generating UWB monocycle and triplet pulses, as shown in Fig. 2. Recall that doublet pulses can be shaped directly at the output of the NOLM by adjusting the PC; therefore, only one branch of the balanced PD is needed to convert the pulses from the optical domain to the electrical domain. Using the combination of the NOLM and balanced PD, monocycle, doublet, and triplet pulses can be obtained using our proposed setup.

Figure 3 shows the experimental setup for our proposed reconfigurable UWB pulse generator. An external cavity laser (ECL) at 1559.7 nm is modulated using a Mach-Zehnder modulator (MZM) driven by a pulse pattern generator (PPG) to create a train of Gaussian-like pulses with a repetition rate of 2.5 GHz. The Gaussian pulse train is then amplified by an EDFA
and launched into the NOLM through a WDM coupler (WDM 1). A second WDM coupler (WDM 2) is used to remove the pump from the NOLM. The HNLF used in the NOLM has a length of 1007 m with a nonlinear coefficient of 12.5 W⁻¹km⁻¹, a chromatic dispersion of 0.02 ps/(nm⋅km) at 1550 nm, and a dispersion slope of −0.01 ps/(nm²⋅km) at 1550 nm. We use PC2 to control the SOPs of the pump and probe, and hence the NOLM transfer function, to obtain either wavelength conversion or doublet pulse generation from the Gaussian pump. A probe signal at 1539.1 nm from a second ECL (ECL2) is injected into the NOLM through 3-dB coupler 1. The output of the NOLM is divided into two branches: one is connected to an OTDL for relative delay adjustment, while the second is connected to a variable optical attenuator (VOA) to adjust the power level. After differential detection using a 40 GHz balanced PD, both time-domain waveforms and electrical spectra are measured by a digital communications analyzer (DCA) using an electrical sampling module with a bandwidth of 80 GHz and an electrical spectrum analyzer (ESA) with a bandwidth of 40 GHz.

3. Results and discussion

![Fig. 4.](image)

Fig. 4. (a), (c), (e), (g) Measured waveforms and (b), (d), (f), (h) corresponding RF spectra of the generated UWB monocycle and doublet pulses. (RBW: 300 kHz)

To generate UWB monocycle pulses, we bias the NOLM to function as a wavelength convertor. In this case, the pump power was amplified to 12.4 dBm while the probe power was set at 2 dBm. By adjusting the relative delay and power levels prior to differential detection, UWB monocycles are obtained at the output of the balanced PD. The time domain waveforms and corresponding RF spectra are shown in Figs. 4(a)-4(d). We use the normalized FCC mask (red-dash line) which is normalized to the RF components with maximum power in the region from 3.1 GHz to 10.6 GHz to illustrate how well the spectra of the generated UWB waveforms comply with the FCC mask [9]. Note that polarity-inverted monocycle pulses can be obtained by tuning the OTDL. The center frequency and 10 dB bandwidth of the generated UWB monocycle pulses are approximately 4 GHz and 9.5 GHz, respectively, yielding a fractional bandwidth of 212.5%. To generate UWB doublet pulses, as mentioned above, PC2 was adjusted to control the NOLM transfer function accordingly and only one branch of the balanced PD was connected to the NOLM output. The polarity of the doublet pulses can be reversed by exciting the appropriate branch of the balanced PD. The results are shown in Figs. 4(e)-4(g). The central frequency is 8.8 GHz and the 10 dB bandwidths of the polarity-inverted doublet pulses are 9.5 GHz and 11 GHz, corresponding to fractional bandwidths of 107.9% and 137.5%. It is known that the RF spectra of the monocycle pulse and doublet pulse cannot fully satisfy the FCC mask; however, the main spectral content lies within the FCC mask, so that the waveforms can be used in less power-critical applications. In our proposed system, in addition to UWB monocycle and doublet pulses, more complex waveforms such as triplet pulses can also be generated. By biasing the PC within the NOLM and enabling the two branches of the
balanced PD, we obtain UWB triplet pulses as shown in Fig. 5. Clearly, the RF spectra of the
triplet pulses satisfy the FCC mask fully, compared with the monocycle and doublet pulses
without modulation. The central frequency and 10 dB bandwidth are 7.5 GHz and 8.7 GHz,
respectively, and the fractional bandwidth is 116%. Note that for modulated UWB signals, such
as the OOK modulation, the RF spectrum will exhibit frequency spectral content below 2.5
GHz, as shown in Figs. 6(a)-6(b). These lower-frequency components may not be easily
handled in the optical domain. However, they can be suppressed by exploiting well-designed
antennas, e.g., those that have a frequency response with a flat top in the UWB band and a deep
notch in the lower-frequency region [26]. In order to evaluate the transmission performance of
our proposed UWB pulse generator, we have also performed a bit-error-ratio (BER)
measurement for OOK-modulated doublet pulses over 10-km standard single mode fiber
(SSMF). The eye diagrams, RF spectra, and BER performance are shown in Fig. 6. The 10 dB
bandwidth and central frequency are maintained well. Meanwhile, we can obtain an error-free
transmission with a power penalty of around 1.6 dB, compared with the back-to-back
measurement.

A flexible UWB pulse generator must have the capability to implement various modulation
formats upon request. The flexibility of our scheme enables most existing modulation formats.
In addition to OOK modulation demonstrated above, the pulse shape can be switched between
monocycle and triplet pulses by tuning PC2, yielding the possibility for implementing PSM. To
achieve high-speed PSM, we can replace the PC2 inside the NOLM with a polarization
modulator (PolM) sandwiched by two PCs to realize PSM. After setting two PCs properly, the
phase shift \( \psi \) induced by the PolM will follow the same operation principle in order to realize
wavelength conversion or nonlinear pulse shaping. Therefore, by applying the data signal to the
PolM, we can realize high speed PSM. Currently, the speeds of commercial PolMs can operate fast as 40 Gb/s [27], which is sufficient for our scheme. As demonstrated in section 3, polarity-inverted UWB pulses can be obtained. These features are attractive as the proposed setup can be easily applied to BPM with monocycle and triplet pulses by adjusting the OTDL. Switching times below 10 µs based on thermal tuning were demonstrated in [28]. According to state-of-art techniques, rapidly tunable delay lines can be implemented, using electro-optic effects (via p-n junction diodes) in a rib waveguide-based OTDL [29]. Currently, PPM is another commonly used modulation format for UWB communication system [30]. Our architecture is also compatible with such modulation formats. As shown in Fig. 3, a length of standard single mode fiber (SSMF) can be added at the output of the NOLM. The pulse position can be controlled by tuning the output wavelength of ECL2, according to the linear relationship between time delay and wavelength difference. Therefore, PPM in electrical domain can be achieved at the output of the PD. Note that the time resolution is determined by the wavelength tuning resolution of ECL2, which is typically 1 pm. In order to make the setup more compact, a specially designed chirped fiber Bragg grating with the required dispersion value can be used to replace the SSMF. Since XPM arising in the HNLF has an ultrafast response time, the reconfiguration time of the UWB pulse generator is mainly determined by the PC, OTDL and the optical switches.

In fact, the proposed approach is able to produce doublet pulses with different polarity simultaneously by simply adding a circulator at the reflection port of the NOLM [21]. When a doublet pulse is formed at the output of the NOLM, a polarity reversed pulse is also formed at the reflection port due to the power conservation of the probe. This feature makes the UWB generator more flexible than the one based on the nonlinear transmission function of MZM [20]. Compared with the NOLM-based UWB pulse generator in [21], we only need 2 laser sources for doublet pair generation. Moreover, the UWB pulses are carried by single wavelength, leading to a better tolerance to fiber dispersion. The proposed UWB pulse generator also has the potential for on-chip integration (e.g., in SOI) by integrating discrete components such as a filter [31], coupler, PC [32], and OTDL [29] with a length of highly nonlinear waveguide in a single chip. Note that silicon-based Sagnac interferometric structures have also been reported [33]. This will lead to further advantages such as stability, small size, high power efficiency, and better tuning characteristics.

4. Summary

We have proposed a reconfigurable UWB pulse generator based on the pulse shaping capabilities of a NOLM combined with differential detection. The generation of UWB monocycle, doublet, and FCC-compliant triplet with inverted polarity has been experimentally demonstrated. Furthermore, we have shown that our proposed scheme can be easily applied to various modulation formats such as OOK, PSM, BPM, and PPM.

Acknowledgments

This work was supported by the National Basic Research Program of China (973 Program: 2010CB328302), the 863 High Technology Plan (2012AA011301), the National Natural Science Foundation of China (61275069), and the Natural Science and Engineering Research Council of Canada (NSERC) via the CREATE program in Next-Generation Optical Networks.