Progress In Electromagnetics Research C, Vol. 65, 103–110, 2016

Observations in Respect of Real Time Temporal Cloaking/Uncloaking at Microwave Frequencies

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Abstract—Based on space-time duality and through the use of temporal dispersive delay lines, this paper presents a demonstration of temporal cloaking/uncloaking at microwave frequencies. Numerical simulations of pulse generation, continuous wave signal recovery and data recovery are discussed in relation to the proposed system architecture. This paper also suggests a practical means for implementation of real time dual temporal cloaking/uncloaking. Compared to traditional signal processing systems, since the recovered data emerges with a reversed form in time domain before its final decoding, an extra operation named time-reversal is needed to obtain the correct data, which could help protect the significant signals better with the proposed temporal cloaking/uncloaking system. The proposed method and achieved results indicate potential application in secure communications and data multiplexing subject to channel bandwidth requirements.

1. INTRODUCTION

The idea of a device which conceals events rather than objects was discussed in 2011 by McCall et al. [1]. Here light was manipulated using an intensity-dependent refractive medium to create a temporal gap within which time events could be hidden. In 2012, Fridman et al. created the conditions [2] that permit temporal cloaking by exploiting the space-time duality associated with diffraction and dispersion [3]. Implementation at optical frequencies used a split time-lens created by Bragg scattering via four-wave mixing with constant frequency pump wave and a linear frequency chirped wave followed by a positive dispersion single mode fiber. This led to red and blue spectral components of the pump pulse becoming delayed with respect to each other and thus forming a temporal gap. Temporal self-imaging through the Talbot effect [4, 5] was used to conceal optical data. In 2013, Lukens et al. succeeded in cloaking 46% of the entire time axis and they concealed pseudorandom digital data at a rate of 12.7 Gigabits per second using an all optical set up [6]. However, the paper did not address data recovery.

The reported systems depend on paraxial diffraction in space and dispersion in time being equivalent [7] so that a time version of a dispersive spatial lens can be constructed, a 'time lens', so-called because it works in much the same manner as a spatial thin-lens. A spatial lens imparts a quadratic phase in space and a time-lens produces a quadratic phase shift in time [8–11]. Time-lenses can compress [12] temporal signal by using mixing of a CW signal with a chirped pump wave which after propagating through a dispersive element creates an impulse.

In this paper we propose a real time temporal cloaking/uncloaking system through constructing corresponding time-lens with the usage of microwave devices. The results demonstrated in this paper further previous work by dual protecting the inserted data in a time-reversed form [13] and achieving data recovery. The numerical analysis is calculated in MATLAB. Practical implementation

Received 3 May 2016, Accepted 11 June 2016, Scheduled 25 June 2016
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issues are analyzed and corresponding conclusions obtained. Taking advantage of the proposed concealed transmission method in this paper, the temporal system has potential applications in secure communications and data multiplexing subject to channel bandwidth requirements.

2. TEMPORAL CLOAKING

Figure 1 shows the schematic of realizing temporal cloaking. After passing through the proposed positive time-lens, the input Continues wave (CW) could be compressed into pulse strings, between which temporal gaps are generated for concealing corresponding events. The pulse string with events inserted could be reconstituted to an output CW after an opponent impact operated by the negative time-lens shown in Fig. 1. The recovered output CW indicates the feasibility of realizing real time temporal cloaking with the proposed method.

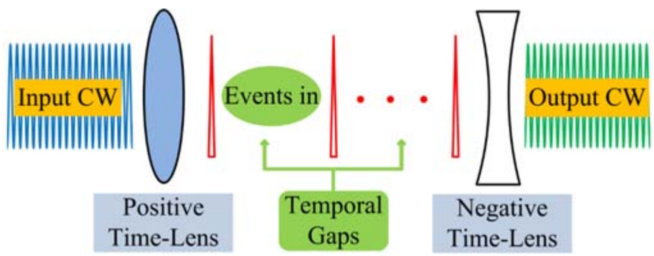

Figure 1. Schematic for real time temporal cloaking.

The schematic for implementation of real time temporal cloaking at microwave frequencies is shown in Fig. 2. At microwave frequencies three terminal mixers are available, as are synthesized frequency sources to generate linear frequency chirp. The chirped dispersive delay line (DDL) is an important technique for chirp signal generation or dispersion compensation which has been widely used in microwave analogue signal processing [14–17] for compressing or expanding time waveforms, which plays the core role of the proposed temporal cloaking/uncloaking system.

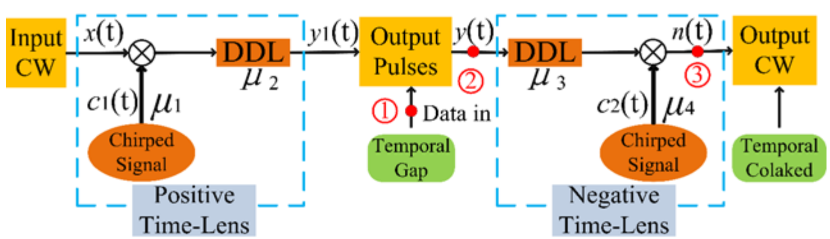

Figure 2. System configuration for temporal cloaking.

In Fig. 2, the sweep coefficients, which are the reciprocal of group delay slopes, of the dispersive delay lines and the chirped signals satisfy the relationship given as $\mu_2 = \mu_3 = -\mu_4 = -\mu_1 \cdot c_i(t)\,(i = 1, 2)$ denotes the chirped signals generated by DDLs with corresponding sweep coefficients. The approximate impulse response of an ideal DDL [18] with an initial frequency at 0 Hz is $h(t) = e^{j\mu t^2}$.

The input continuous wave (CW) signal, $x(t) = e^{j\omega_0 t}$, while passing through the proposed positive time-lens will firstly mix against a chirped signal (with sweep coefficient μ_1) to get a quadratic phase modulation on it, and then pass into the dispersive channel in order to generate impulses according to the Equation (1)

$$y_1(t) = x(t) \cdot e^{j\mu_1 t^2} * e^{j\mu_2 t^2} = e^{-j\mu_1 t^2} \cdot \int x(\tau) \cdot e^{2j\mu_1 t\tau} d\tau \tag{1}$$

The asterisk denotes convolution. With the theory of Fourier transform and the property of Dirac delta function, Equation (1) could be re-written as

$$y_1(t) = \frac{\pi}{|\mu_1|} e^{-j\frac{\omega_0^2}{4\mu_1}} \delta\left(t + \frac{\omega_0}{2\mu_1}\right) \tag{2}$$

Dispersive line with sweep coefficient μ_2 acts so as to make long wavelengths in the chirped input CW signal travel further than the shorter wavelengths. This allows the shorter wavelengths to catch up with the longer wavelengths and thus at the output of the dispersive line with sweep coefficient μ_2, the frequency components add in phase to form an impulse as expressed in Equation (2).

According to the proposed system, impulse trains can be achieved by periodically repeating the chirped signals, and temporal gap occurs between adjacent impulses. In order to achieve $K+1$ periodic impulses, the generated chirped signal for each temporal gap with sweep coefficient μ_1 should satisfy the condition expressed in Equation (3),

$$c_1(t) = e^{j\mu_1(t-kT)^2}, \quad t \in [kT, (k+1)T], \quad k = 0, 1, 2, \ldots, K \tag{3}$$

where T equals to the time length of the first chirped signal and acts as the period of the repeated chirped signals, then $y_1(t)$ becomes as follows,

$$y_1(t) = \sum_{k=0}^{K} \frac{\pi}{|\mu_1|} e^{-j\frac{\omega_0^2}{4\mu_1}} \delta\left((t - kT) + \frac{\omega_0}{2\mu_1}\right) \tag{4}$$

which has $K+1$ Dirac delta impulses distributed with a period of T and forms K temporal gaps between adjacent impulses. Taking the first temporal gap for example, data would be inserted to $y_1(t)$, and $y(t)$ given in Equation (5) is defined as the coded signal.

$$y(t) = y_1(t) + y_{\text{data}}(t) = \frac{\pi}{|\mu_1|} e^{-j\frac{\omega_0^2}{4\mu_1}} \delta\left(t + \frac{\omega_0}{2\mu_1}\right) + y_{\text{data}}(t), \quad t \in \left[-\frac{\omega_0}{2\mu_1}, -\frac{\omega_0}{2\mu_1} + T\right) \tag{5}$$

Then we move to the negative time-lens, which would help recover the input CW signal from the generated impulses and the expression for the reconstituted signal, $n(t)$, can be written as

$$n(t) = \frac{\pi}{|\mu_1|} e^{-j\frac{\omega_0^2}{2\mu_1}} \cdot e^{-j\omega_0 t} + \int y_{\text{data}}(\tau) \cdot e^{-j\mu_1(\tau - 2t)\tau} d\tau \tag{6}$$

Comparing $n(t)$ to the input CW signal $x(t)$, $n(t)$ is dominant by a CW signal with the same frequency as the input one, multiplied by a constant. Thus we can speculate that the proposed structure illustrated in Fig. 2 could help implement temporal cloaking.

In this paper the input continuous wave (CW) signal is a sinusoidal signal with a frequency of 3 GHz which will be intercepted by the first chirped signal with a same time period for signal analysis. Here we choose $\mu_1 = -1$ GHz/ns with a period of 10 ns to help generate pulse strings according to Equation (3). A randomly chosen data pattern 101101, whose minimum pulse duration is 1ns as shown in Fig. 3(a), is inserted between 12 ns and 18 ns in the first temporal gap (9.4 $\sim$ 19.4 ns), the first two generated pulses are at the time slot of 9.4 ns and 19.4 ns respectively. Fig. 3(b) shows the first two generated pulses with data inserted.

Due to the influence of rectangular window function to the input CW signal, ripples introduced around the generated impulses have impacted on the inserted data, as depicted in Fig. 3(b) and parts of the input data signature have been transferred to the output CW signal as shown in Fig. 3(c). As illustrated in Fig. 3(c), the proposed system permits the input CW to be recovered from the generated impulses and cloaks the data in the reconstituted CW. With no attempt making to suppress the ripple introduced during the impulse compression stage, the correlation between the output CW signal (9.4 $\sim$ 29.4 ns) and the intercepted input CW signal (0 $\sim$ 20 ns) is 0.85. At microwave frequencies it is possible to generate very narrow impulses electronically [19]. If ideal impulses are introduced at timing slots identical to those generated by the compression stage, the cross correlation between the output CW and the input CW is improved to 0.93, which indicates that temporal concealing would largely occur and data inserted in the temporal gap could not be easily detected. Correlation coefficient is a significant metric throughout this paper for measuring the effect of temporal cloaking. The purpose of this research is to improve the correlation coefficient which could reflect the reduced error rate in final uncloaking.

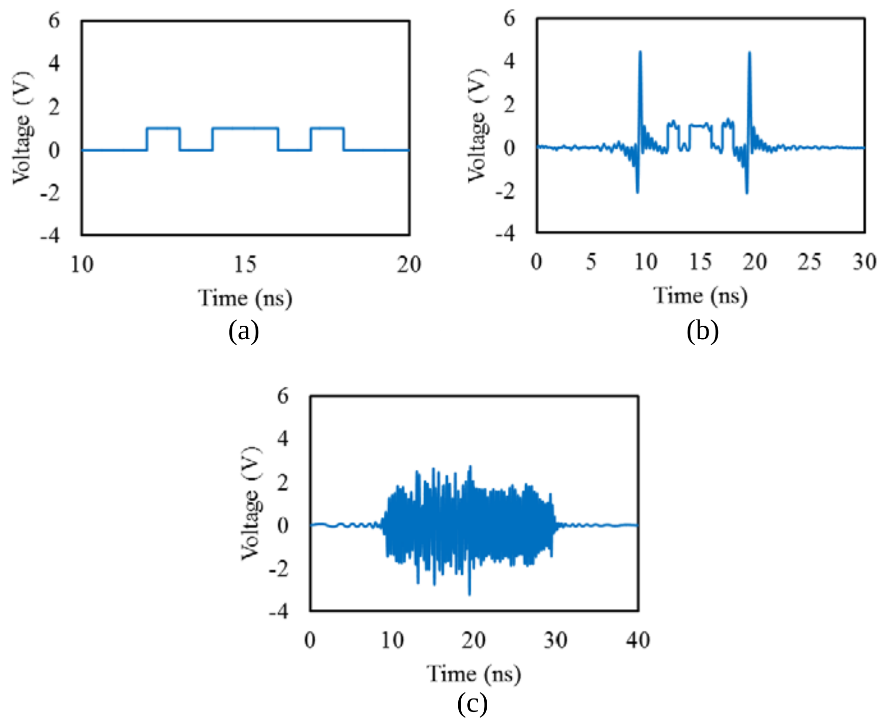

Figure 3. (a) Inserted data pattern, (b) generated pulses with data inserted and (c) reconstituted output CW with data inserted.

3. DATA INSERTION AND TEMPORAL UN-CLOAKING

Figure 4 shows the schematic system for realizing event detecting from the cloaked signal $n(t)$.

The sweep coefficient in this system satisfies the relation as $\mu_5 = -\mu_6 = \mu_1$ and the output signal can be expressed as

$$o(t) = n(t) \cdot e^{j\mu_5 t^2} * e^{j\mu_6 t^2} = \frac{\pi^2}{\mu_1^2} \cdot e^{-j\frac{3\omega_0^2}{4\mu_1}} \cdot \delta\left(t - \frac{\omega_0}{2\mu_1}\right) + \frac{\pi}{|\mu_1|} \cdot e^{-2j\mu_1 t^2} \cdot y_{\text{data}}(-t) \tag{7}$$

Comparing the expressions for $y(t)$ and $o(t)$, we achieve recovering the generated impulses as well as the inserted data $y_{\text{data}}(t)$ both in a reversed form in time domain. Thus on the basis of the proposed system, we could not only achieve temporal cloaking/uncloaking, but also dual protect the inserted data in a time-reversed form. This property indicates that only if the cloaked signal has been reversed

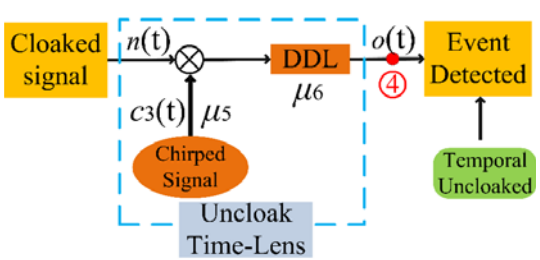

Figure 4. System configuration for realization of temporal uncloaking.

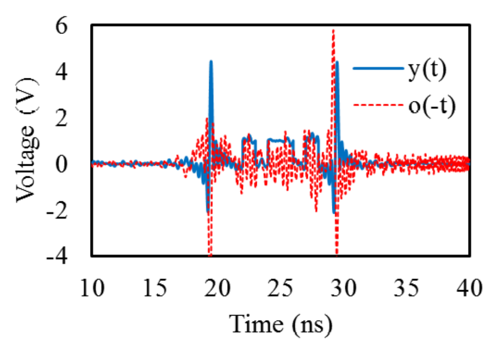

Figure 5. Comparison between the coded impulses and the time-reversed uncloaked impulses.

in time-domain can the final correct decoded data be obtained, otherwise the demodulated information would mislead the subsequent analysis. The time-reversal operation and a time-gate are needed to help extract the coded data from the regenerated impulses $o(t)$.

The blue line in Fig. 5 shows the generated pules with data inserted, and the red dot line is the uncloaked pulses with decoded data in time-reversed form. The cross correlation between the inserted data and the time-reversed recovered data with no decision making is 0.84. The results demonstrate that it is possible to achieve temporal uncloaking through the meaningful arrangement suggested in Fig. 4. Actually, according to the proposed cloaking system in this paper, before sending to the uncloaking system, the inserted event can be permanently cloaked in the recovered CW signals.

In computer simulations and further experimental analysis, the chirped signals generated by corresponding dispersive delay lines are described by their impulse responses with an initial frequency at 0 Hz as [17],

$$h^R(t) = \cos\left(2\pi\mu t(t-T)\right), \quad 0 \leq t \leq T \tag{8}$$

Figure 6 shows the corresponding results of inserting different data sequences between every space of the ideal impulses. We allow the data amplitude as shown in Fig. 6(a) to vary in order to see if this variation can be recovered. The cross correlation between the input CW and the output CW with codes added is 0.77. The result shown in Fig. 6(b) verifies the possibility of interleaving and then recovering multiple data series and the possibility of preserving data amplitude variation as might occur in a higher order modulation scheme through the mentioned temporal cloak/uncloaking system. Additionally, when the condition that the amplitude of the inserted data is significantly lower than that of the generated impulses is satisfied, $y_{\text{data}}(t)$ could spread and thus be cloaked within the recovered signal $n(t)$.

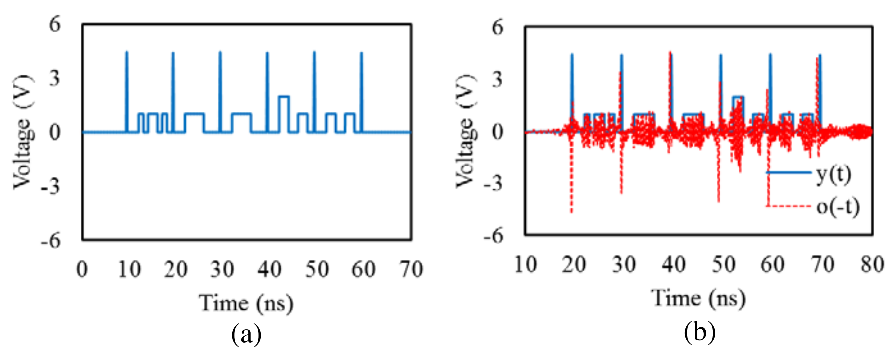

Figure 6. (a) Ideal impulses with data series inserted and (b) comparison between the coded impulses and the time-reversed uncloaked impulses.

4. PRACTICAL IMPLEMENTATION CONSIDERATIONS

Furthermore, we use qualified chirp generators to help produce corresponding chirped signals required in proposed systems, and then numerically replace the dispersive delay lines by a reflection-type dispersive delay line [20] with a group delay slope of −0.5 ns/GHz and $|S_{11}| > -0.5$ dB ranging from 6 to 15 GHz. The proposed dispersive delay line is designed on a substrate with a dielectric constant of $\varepsilon_r = 10.2$ and a thickness of 0.5 mm, the total length of the structure is 320 mm. Fig. 7(a) and Fig. 7(b) show the group response and S parameter of the designed dispersive delay line respectively.

Since the parameters of the proposed dispersive delay line is of the best response.

Because of the wide working band and linear group delay response of the designed DDL while $|S_{11}| > -0.5$ dB, when the parameters are numerically installed into Fig. 2, after CW signal reconstitution the cross correlation between the input CW signal and the output CW signal is 0.81. As before if the input impulses are artificially introduced at the appropriate time segments, Fig. 8(a) shows the corresponding results of inserting 2 different data between every space of 3 ideal impulses according to the results of the reflection-type DDL used everywhere else in the system. By setting qualified time-gate and implementing time-reversal operation, Fig. 8(b) offers the comparison between the final decoded data

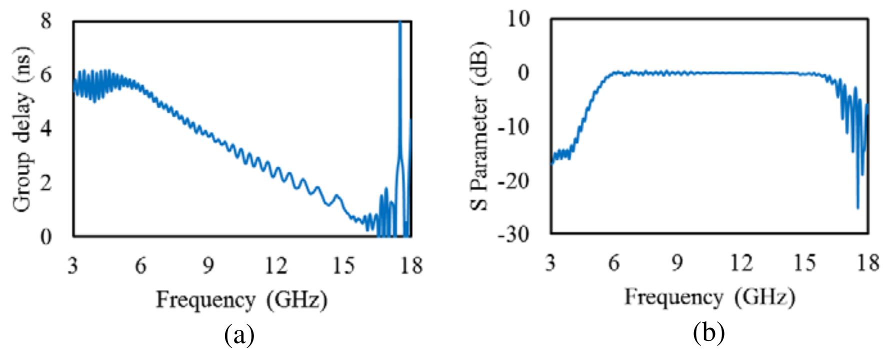

Figure 7. a) Group delay response and (b) S-parameter of the designed DDL.

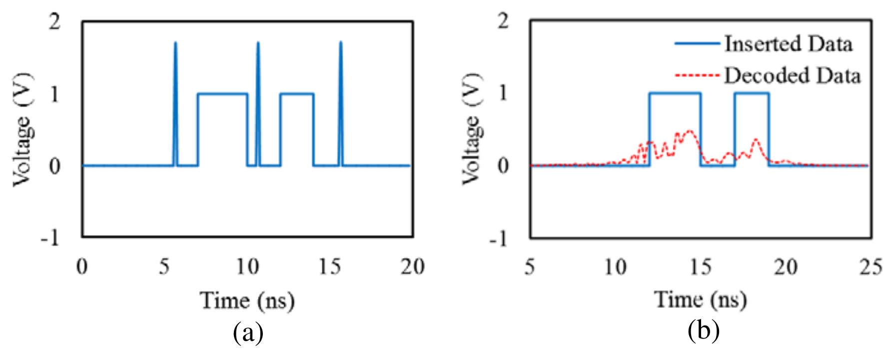

Figure 8. Results for practical implementation considerations: (a) The ideal form of the generated impulses with inserted data series and (b) comparison between the inserted and final decoded data.

and the inserted one. Here it can be seen that the final decoded data occurs at the appropriate position in the relevant time slot, and the correlation between the inserted and decoded data is 0.68.

The results shown in Fig. 8(b) verifies that temporal uncloaking of more data inserted in different temporal gaps could be realized correspondingly. However, obvious loss happens to the decoded data while compared to the inserted one. The main causes are that the group delay response of the designed DDL is not absolutely smooth [20] and the useful time delay length is not long enough as depicted in Fig. 7(a) and Fig. 7(b).

The above study indicates that in order to improve these correlation coefficients, the DDLs for using in these systems should exhibit (i) long delay time duration, (ii) large slope (ns/GHz), and (iii) smooth group delay response.

5. CONCLUSION

In summary, some primary issues related to creating a real time temporal cloaking/uncloaking system which can operate at microwave frequencies has been presented in this paper for the first time. Corresponding numerical simulations have been discussed in relation to the cloak and uncloak system architectures. With an essential extra operation called time-reversal implementing to the un-cloaked signal and through putting parameters of designed dispersive delay lines into the numerical analysis system, we show a predictable practical implementation of real time dual temporal cloaking/uncloaking. The proposed method is potentially suitable for secure communications as well as advanced data interleaving operations provided the spectrum spread introduced by the system can be accommodated by the communications system through which the cloaked data is to be sent. With the results shown above, this paper has proposed and verified a new method of realizing temporal cloaking, which could be used in secure communications. Since another time-reversal operation is needed for achieving the final decoded data, the proposed system is superior to traditional secure communication systems for it could automatically dual-protect to the inserted data. Additionally, the dispersive delay line plays a core role throughout the cloaking/uncloaking system, relationships among each sweep coefficient help protect the inserted data and increase the difficulty in data decoding. Since it is unlike at optical frequencies where various strategies exist for creating dispersive delay lines with extremely long delay times and ultra-wideband wideband couplers exist, the demands on the DDL at microwave frequencies are significant. The effects that dispersive delay lines and chirp shaping have on recovered inserted data integrity need further investigation. It is hoped that this paper will encourage others to engage with this new and potentially important topic in secure communications.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (Grant Nos. 61331007, 61361166008, and 61371106), the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20120185130001), and the China Scholarship Council of 2013.

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