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Electronic Simulation of the Temporal Characteristics of Photon Memory Echoes and Some Related Applications

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ABSTRACT

The characteristics of nonlinear photon memory echoes are investigated by means of SPICE s imulations using equivalent resonator ensembles. By developing implicit nonlinear circuit models in the memory echo domain, the triple product formalism of electronic holography, involving correlation and convolution, is tested for the storage and recall of arbitrary signals and/or data bit streams in both time-inverted and nontime-inverted modes. Furthermore, a few specific optical data processing applications are also simulated in which the mixed binary multiplication of two or more binary bit streams is achieved. Higher order products, optical pattern recognition, and other possible applications are also discussed. It is shown that much insight into the nature and scope of optical photon echoes as memory storage phenomena may be derived using the electronic simulation technique.

1. BRIEF BACKGROUND AND INTRODUCTION

Various types of echoes have been studied in connection with nonlinear signal storage phenomena, including for instance, spin echoes, ferrimagnetic echoes, cyclotron echoes, plasma echoes, molecular echoes, phonon echoes (in piezoelectric crystals and powders), and photon echoes. A comprehensive review of the investigations in this field can be found in reference [1].

A key concept in the formation of nonlinear echoes, or storage in general, is the notion of phase conjugation. Through the Fourier transform, phase conjugation in the frequency domain is connected with time reversal in the time domain. It provides us with an inkling of how echoes could come about: If, through phase conjugation, time is "reversed" τ seconds after an event, it will occur again after a second interval of τ seconds. Furthermore, nonlinearity is required to cause phase conjugation; in particular, an odd-order nonlinearity.

The first attempt at a unified theory appears to have been due to Korpel [2]; in this theory, the nonlinear system is visualized as a wideband collection of propagating eigenmodes or resonant frequencies, which essentially act as a physical Fourier Space in which the spectral characteristics of a signal are preserved by means of a mechanism reminiscent of optical holography. The formalism, with relatively minor modifications, has been shown previously to explain most of the observed nonlinear echo phenomena as well as predict a few new ones in the dynamic as well as static regimes. In section 2, the characteristics of general dynamic and static echoes are introduced briefly. Furthermore, the theory of parametric echoes, proposed by Korpel [2], and extended by Chatterjee [3], is introduced with its natural prediction of signal correlation and convolution via the triple product [1,2,3].

In section 3, we carry out an introductory review of the derivation of nonlinear equivalent circuits to adequately model parametric coherent echoes based on the so-called electronic holography formalism due to Korpel and Chatterjee [3,4]. We restrict ourselves to circuit modeling strategies for dynamic echoes with nonlinear coupling, and, especially, to an implicit nonlinear circuit modeling strategy for static three-pulse and general signal echoes in an N-element ensemble which is used to perform our SPICE simulation experiments.

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In section 4, we discuss some experimental results associated with photon memory echo storage and processing as a prelude to our own circuit simulation results, since the characteristics of photon dynamic and memory echoes are closely related to the parametric echo or electronic holography formalism. An important difference between a photon echo and other parametric echoes is that we need to consider the propagation direction of photon echo because of its spatial effect. The direction of photon echoes can be predicted by using a k-vector scheme [5,6,7]. Recently, the backward-stimulated photon echo (BSPE) [8,9], which is a stimulated-echo scheme using a counterpropagating excitation geometry, has been found to be especially useful for optical information storage because the echo can be spatially and temporally separated from the excitation pulses. The generation of a backward-stimulated photon echo and its applications in a solid sample have been reported recently [10,11].

In section 5, by first using the theory of parametric echoes, and N-resonator ensembles for static memory echoes, we investigate the characteristics of nonlinear photon memory echoes. We remove undesirable nonlinear and linear echoes far from the nonlinear memory echo by using nonuniformly-spaced linear resonator ensembles [12]. Secondly, the triple product formalism of electronic holography, involving correlation and convolution, is tested by applying two or three rectangular pulses to the modeled circuit in the memory echo domain. Arbitrary signals, such as a sawtooth pulse and a rectangular pulse, and data bit streams are stored and recalled in each of three possible configurations for a general signal and two delta pulses in both time-inverted and nontime-inverted modes. Only a few examples of these simulations will be provided here. We have also investigated the amplitude and time limitations for data bit stream storage and retrieval. Finally, a specific optical data processing application is also simulated in which the mixed binary multiplication of two or more binary bit streams has been achieved. We present two specific examples of this application. The SPICE simulation results are generally in good accord with the experimental results reported for photon echo applications [10,11,13].

In section 6 we conclude this paper with some comments on the overall SPICE performance, its feasibility and limitations. Some further research is also discussed by comparing the current approach with photon echo experimental results reported recently. More explicit and extensive results from this research will be reported in a detailed paper elsewhere.

2. CHARACTERISTICS OF NONLINEAR DYNAMIC AND STATIC ECHOES

Echo effects [1] occur in nonlinear systems that are characterized by a multiplicity of resonant states or eigenmodes. When such systems are excited by a sequence of high energy RF pulses, they subsequently re-radiate, through nonlinear processes, RF power in the form of echo pulses that bear observable relationships to the exciting pulses. Such echo pulses are a specific instance of more general storage and recall.

In the short-term or dynamic echo (also called a two-pulse echo), such as a spin echo, a photon echo, a ferrimagne tic echo, a cyclotron echo, or a plasma echo, it has been established that the mechanism for echo generation resides in the parametric interaction of a collection of resonators or eigenmodes with an applied electric field in the presence of an odd-order nonlinearity. The nonlinearity is commonly manifested in the excitation amplitude, or, in some cases, in an amplitude-dependent shift of the oscillator or mode frequencies. In either case, the result is that the system, excited at $t=0$ by a "WRITE-IN" pulse, followed at $t=\tau$ by a "recall" ("READ") pulse, undergoes phase conjugation in the frequency domain, which in the time domain, leads to a physical reversal of the signal in space and time, thereby producing at $t=2\tau$ an "echo" of the "WRITE-IN" pulse. The twin processes of phase conjugation and time reversal are the underlying mechanisms in virtually all dynamic system.

All the echoes mentioned up to this point are of a dynamic nature. The second pulse must be applied before the oscillations excited by the first one have died out or otherwise irreversibly dephased. However, we also could observe three-pulse echoes. As shown in Fig.2.1, in the latter case pulses are applied at $t=0$, τ, T, whereupon an echo will appear at t=T+τ in addition to the usual one at t=2τ. The mechanism of echo formation is basically the same, as can be demonstrated by considering the effect of a cubic nonlinearity on the three pulses:

$$[A_1\cos(\omega t)+A_2\cos(\omega t-\omega\tau)+A_3\cos(\omega t-\omega T)]^3 \quad , \tag{2.1}$$

which contains a term $\propto A_1A_2A_3\cos(\omega t-\omega\tau-\omega T)$.

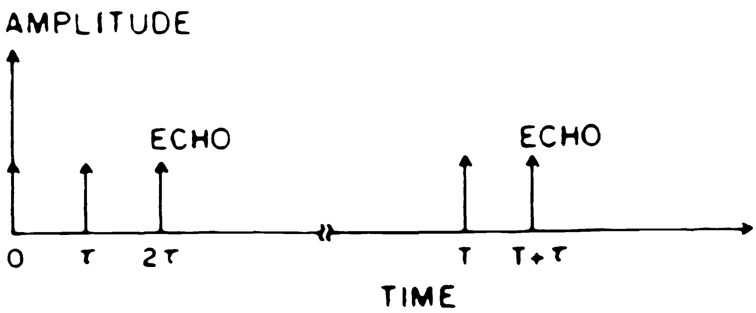


Fig.2.1 Typical sequence for a two- and three-pulse echo. (after Korpel and Chatterjee [1])

We now come to a class of echoes where this behavior is no longer similar but may, in fact, be vastly different. Three-pulse echo relaxation times have been observed that to all intents and purposes are infinite. Obviously, some quasi-permanent storage must have been effected by the first two (WRITE) pulses so that, as in a hologram, information may be read out much later by a third (READ) pulse.

Long-term or static echoes (also called three-pulse echoes), such as photon echo, phonon echoes in crystals and powders, have been investigated in the past decades. Between 1970 and 1973 several investigators reported the observation of RF echoes in single crystal and polycrystalline piezoelectric or ferroelectric materials. Besides, the first (dynamic) echoes due to acoustic resonances of individual powder particles were observed and interpreted in 1968 and, later, the anomalous persistence of these echoes in powders was first reported in 1975. The discovery led to the possibility of obtaining very long and stable memories in powders.

It is interesting to note that the memory mechanism outlined above could well be called "electronic holography" or "parametric echo" [2]. As in optical holography [14], both the phase and amplitude of a spectral component of E_1 (plane wave spectrum in optics) are stored by recording the pattern of interference ($\cos\omega\tau$ in the electrical case) with a signal E_2. The recording takes the form of a change in the coupling parameter:amplitude transmission in optics, angle between dipole and field in electronics. A third "READ" signal acts via the coupling parameter to reconstruct the original signal.

A phenomenological theory of parametric echoes was developed by Korpel in 1978 [2] to explain the dynamic echo. In this theory, the system of independent oscillators or propagating eigenmodes is visualized as a

"Fourier Space", where the spectral components of an input signal are preserved physically by the individual particles or modes. The merit of the parametric formalism lies in the fact that in addition to explaining dynamic pulse echoes, it may also be used to explain the storage and recall of any general signal e(t) of finite duration. If $\phi(\omega)$ is the frequency spectrum of e(t), it may be shown that, for a cubic nonlinearity, the spectrum of the parametrically generated signal E"(t) is proportional to $\phi^2\phi^*$, where the star denotes complex conjugate. In the time domain, this corresponds to a triple product involving correlation and convolution. In particular, if e(t) consists of a arbitrary, finite-duration signal $e_1(t)$ and a delta pulse, then E"(t) is shown to represent a delayed time-reversed version of the signal $e_1(t)$ itself. It is also interesting to note that the triple product formalism is analogous to the one use in Fourier holography, if $\phi(\omega)$ is taken to represent the sum of the reference wave and signal wave.

Furthermore, the parametric formalism can be used to analyze the long-term or memory echo as well. By assuming that the coupling factor K to the individual oscillators is modified by the input signal e(t) as $\Delta K \propto |\phi(\omega)|^2$, the recalled signal E"(t) can be shown to involve a correlation and convolution triple product of e(t) and $e_r(t)$, where $e_r(t)$ is the recall pulse applied at t=T. If e(t) consists of two well-separated function $e_1(t)$ and $e_2(t-\tau)$, the useful part of the recall signal in this case will be a nontime-inverted replica of e_2 centered at $t=T+\tau$, whenever e_1 is a delta pulse.

The implications of the above results are significant. From the mathematics of the parametric formalism, as well as the physics of nonlinear echoes, it is clear that such phenomena can be used in novel methods of signal processing, like convolution, correlation, frequency-selective storage, pulse compression, wavefront reconstruction, and permanent storage and recall of arbitrary signals. Here we use the parametric formalism involving correlation and convolution to implement photon echo storage and processing. The results are summarized in sections 3 and 4.

3. CIRCUIT MODELING STRATEGIES

To demonstrate dynamic and static memory storage and applications by nonlinear simulation using circuit models applicable to SPICE, several systems have been developed, with each circuit configuration representing a specific type of storage and recall [2,3]. The most versatile of these configurations is briefly introduced as follows:

3.1 Dynamic echoes with nonlinear coupling:

As mentioned in the references [2,3,4], a typical nonlinearly coupling RLC stage with an isolated dependent (nonlinear) source is shown in Fig.3.1. In this system, the input stage consists of a linear tuned circuit whose response is coupled to the output through a dependent voltage source f(V), expressible as an arbitrary power series in V. The advantage of this design is that any coupling or feedback between the output stage and the input stage is now eliminated, except, of course, through f(V) itself. This simplifies the prediction of the behavior at the common output node, both mathematically and physically.

In this manner, each RLC stage in an ensemble of such resonators would represent, for instance, a single resonating grain in an ampoule of piezoelectric powder or a mode in a multimode wave system. The order of the nonlinearity is readily controlled by choosing the series coefficients in the expansion of f(V). The simulations [2,3] use (a) $f(V)=a_1V$, to illustrate the elimination of linear echoes in incommensurate ensembles, and (b) $f(V)=a_3V^3$, to show that nonlinear echoes are generated regardless of resonator spacings with complete/partial suppression of any adjacent interfering response. The center frequency of the resonator ensemble would correspond to the average grain size of the resonating powders or the physical dimension of the multimode system. One might intuitively anticipate that the spread of resonances, which would correspond to the distribution of powder grains, is likely to be nonuniform in a physical sample. This further justifies the use in incommensurate resonators in the modeling, an idea which has been introduced earlier [12].

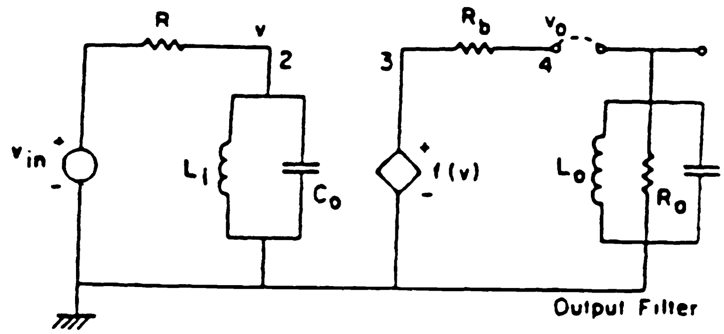


Fig.3.1 Typical nonlinear output coupling configuration.
(after Chatterjee and Korpel [4])

3.2 Static (memory) echo modeling:

Stimulated, static, or memory echoes are simulated using an ensemble of implicit linear resonators with coupling factors adjusted in proportion to the energy in the corresponding input spectral components. A typical circuit configuration [3,4] used for generating memory echoes (which have been used extensively in the work reported here, specifically in section 5), is shown in Fig.3.2.

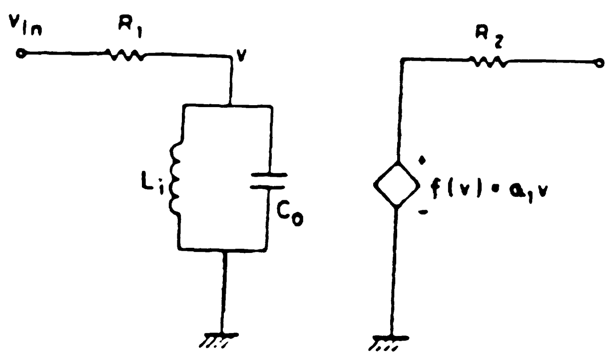


Fig.3.2 Typical circuit configuration used for generating memory echo.
(after Chatterjee and Korpel [4])

To design an N-element SPICE experiment ensemble in which each element or resonator has a different resonant frequency and coupling parameter, we use the general scheme shown in Fig.3.2. Although in previous simulations, the outputs of individual resonators were physically tied together [2] to achieve their sum, we decided to further improve the design (for arbitrary impedance conditions) by summing the outputs through an operational amplifier. Since an OP AMP cannot be directly incorporated in the SPICE domain, we used an equivalent OP AMP model to achieve the same result. A block schematic of our final memory echo system is shown in the above figure. To design the "a_1" values in the ensemble, we first computed the spectral amplitude of the "write-in" signal, e(t). Thereafter, values of the coupling parameters a_1 in the implicitly linear circuit shown in Fig.3.2 were evaluated in accordance with the equation

$$\Delta K = a_l(\omega_l) = K_1 |\phi(\omega_l)|^2 \quad , \qquad l=1,2,3......N \tag{3.1}$$

where $\phi(\omega_i)$ is the spectral component of the "WRITE-IN" e(t) at $\omega=\omega_i$. From this perspective, the N-element system is visualized as a "Fourier Space", where the spectral components of an input signal, e(t), are preserved permanently by the ensemble of resonators. A third,"recall" (READ) pulse, $e_r(t)$, is applied to the linear ensemble of N parallel resonators to the common input of Fig.3.2 at t=T, where T is conveniently time-shifted to T=0 [2,3]. Then, the spectrum of the nonlinearly recalled signal, through the cubic nonlinearity, is given by:

$$E''(\omega) \propto |\phi(\omega)|^2 \phi_r(\omega) \quad , \tag{3.2}$$

where $\phi_r(\omega)$ is the spectrum of the recall (READ) signal $e_r(t)$. Thus, the recalled output signal in the time domain is formed by the following interaction:

$$e''(t) \propto e(t) \otimes e(t) * e(t) \quad , \tag{3.3}$$

where $\otimes$ and * denote correlation and convolution. This is essentially the well-known triple product formalism for memory echoes [1,2,3,4]. We need to mention once again, that we used the circuit model in Fig.3.2 to perform most of the research experiments discussed in this paper.

4. PHOTON MEMORY ECHO STORAGE AND PROCESSING:

The photon echo (PE) effect [15,16] is a coherent four-wave mixing of optical pulse in an inhomogeneously broadened medium [13,15]. The first and second excitation pulses are separated by a time interval τ. The duration of this interval should not exceed the transverse (homogeneous) relaxation time T_2 which determines the phase memory of an optical medium. This allows storage of the corresponding population grating. The spectral information contained in these gratings can exist during the population relaxation time T_1 of the medium and may be retrieved using the third pulse. We may note that in some cases, a quasi-permanent storage also takes place, when the recall times can exceed T_1, and in fact approach infinity [1]. Since this optical medium has an inhomogeneously broadened spectrum, a response appears with a time delay τ after the third pulse, and is called a stimulated PE. Nanoseconds and even microseconds are typical values for T_2 depending on the material used (we do not consider condensed matter where dephasing times are very fast). On the other hand, the minimum duration of the interval τ is limited by the time $T_2^*=\delta^{-1}$, where δ denotes the width of the inhomogeneous spectrum. These times fall in the picosecond time scale. This implies that, if sufficiently short optical pulses are used, the information bandwidth is determined by the relation T_2^*/T_2. Not long ago, storage and retrieval of twenty five pulses, based on the stimulated PE effect, were demonstrated [17]. The designers of this optical memory emphasize that, provided the data pulse train is generated by a faster modulator, the number of stored signals can easily be increased up to 10^3 in the framework of the same experimental setup.

The population relaxation time T_1 indicates how long optical information can be stored in the given medium. Its value is usually much larger than T_2. More interestingly, long-term stimulated echoes have also been observed experimentally [15,17]. In these cases, the delay time between the second and the third pulses of the excitation light sequence, i.e., between the data writing and reading phases, can be changed on different time scales: seconds, minutes and even hours.

The storage of optical information via stimulated photon echoes is accomplished through spectral interference created in the storage material on interaction with two (or more) temporally separated laser pulses. This interference, similar to the spatial interference of two coherent beams in holography, contains the complete information about the combined laser pulses [18]. A storage time of several hours was demonstrated in $Eu^{3+}:YAlO_3$ [19].

The ability to process two-dimensional images has been demonstrated recently [8,9]. If Fourier-transformed images are stored, the stored polarization P will be proportional to the product of three transformed images. If, in addition, the echo image is Fourier transformed again on retrieval, then the resulting amplitude of the echo electric field E_e is related to the three input images through the following relations [8,9]:

$$E_e(t) \propto u_1(-x,-y) \otimes u_2(-x,-y) * u_3(-x,-y) \quad , \qquad (4.1)$$

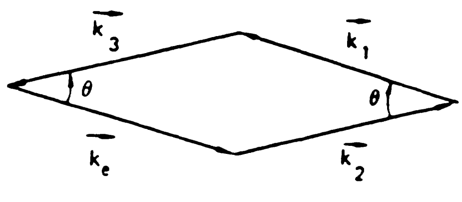
where $\otimes$ and * represent the Fourier correlation and convolution, respectively. Intriguingly, the result in Eq.(4.1) is strangely similar to a temporal triple product originally derived by Korpel [2]. Spatial Fourier transformations can be accomplished by using converging lenses. It is known that if an object mask (used to spatially modulate a laser pulse) is placed at the outer focal plane of a transform lens, the resulting image at the inner focal plane is the exact Fourier transform of the object masks [20]. Thus, input image can be Fourier transformed by use of this lens geometry before storage. When the stored information is later retrieved, it is Fourier transformed back by the lens, the result being an echo image whose electric field amplitude is given by Eq.(4.1). The application of image processing by using stimulated photon echoes, according to Eq.(4.1), have been investigated extensively to demonstrate long-term storage [17], multiple image storage [9], image correlation and convolution [8], pattern recognition [9], mixed binary multiplication [21], and so forth.

In a three-pulse photon echo system, if one chooses the second and third pulses to be counter-propagating, then it may be shown that the echo pulse counter-propagates relative to the first pulse. This particular stimulation leads to the backward stimulated photon echo (BSPE) [17,19]. The BSPE, which is a stimulated photon echo scheme using a counterpropagation excitation, is especially useful for optical information storage because the echo can be spatially and temporally separated from the excitation pulses and from other undesired echo effects.

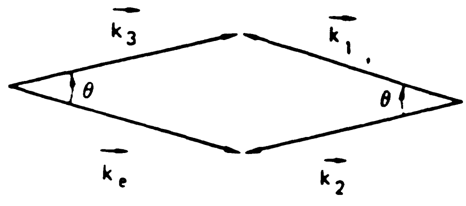
The concept of the backward-echo can be illustrated by the excitation scheme shown in Fig.4.1. Thus, the stimulated-echo amplitude E_e using the k vector relationship of Fig.4.1 is given by:

$$E_e(r) \propto E_1(r) E_2(r) E_3(r) \exp i[-\omega_0 t + k_e \cdot r - \phi_1(r)] \quad , \qquad (4.2)$$

where $k_e=-k_1+k_2+k_3$. If k_2 (the wave vector of the second (write) excitation pulse) and k_3 (the wave vector of the third (read) excitation pulse) are counterpropagating, then $k_e=-k_1$, i.e., k_e counterpropagates with respect to k_1. We can predict that the echo is phase conjugated with respect to the first pulse, regardless of the phase of the other excitation pulses.



(a)



(b)

Fig.4.1 Excitation schemes useful for backward-stimulated echo production in solid. (after Kim and Kachru [11])

5. PHOTON MEMORY ECHO PROCESSING APPLICATIONS: A BRIEF SYNOPSIS

Due to space limitations, we present in this section three results which are representative of the SPICE simulation of the photon and parametric echo modeling technique introduced earlier. As mentioned earlier, the detailed analyses for these cases will be presented elsewhere. Fig.5.1 shows the time correlation of two 4μs rectangular pulses (extending from 0 to 4, and 8 to 12 μs, respectively). As expected, the correlation extends from 4μs to 12μs, and has an isosceles triangle shape.

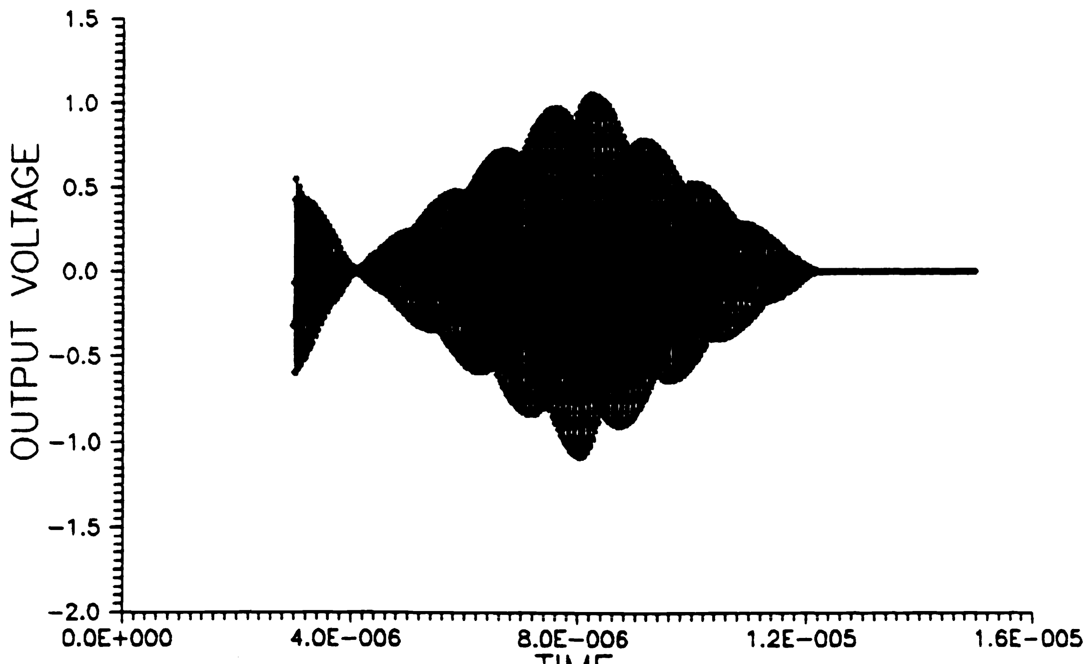


FIG.5.1 TIME CORRELATION OF TWO 4US RECTANGULAR PULSES. N=201,Fc=40 MHz,Fs=25 KHz,V1:V2:V3=2:2:10. TAU=8 US.

Fig.5.2 shows the time-inverted recall of a stored digital data string, 100010101, using 201 resonators with a 40 MHz center frequency, a 25 KHz resonator separation, and a data-bit to recall pulse amplitude ratio of 2:10. It is clear that the recalled data pattern is 101010001.

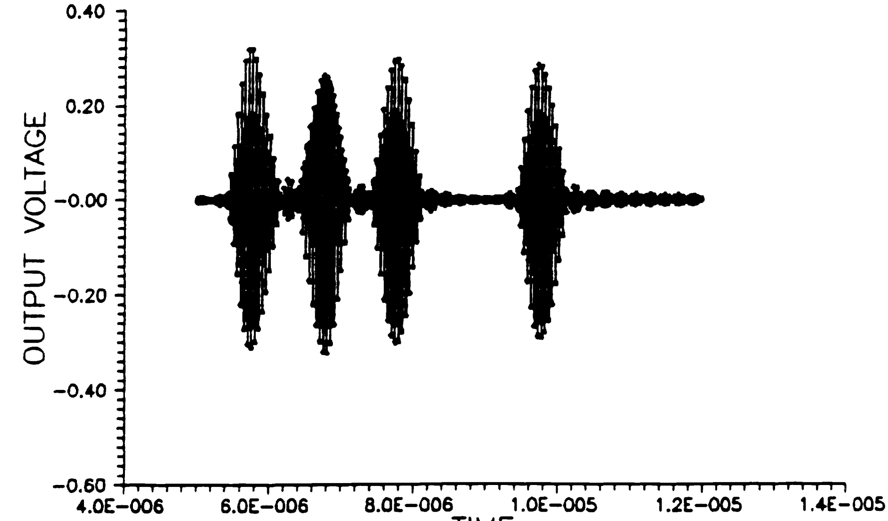


FIG.5.2 TIME-INVERTED RECALL OF STORED DIGITAL DATA (100010101). N=201,Fc=40 MHz,Fs=25 KHz,V1:V2:V3=2:10:10.

Finally, Fig.5.3 shows the mixed binary product of three binary strings, 101, 101 and 11, obtained via SPICE modeling of parametric memory echoes. The zero and one levels were chosen as 0 V and 2 V respectively. Note that the product string 112211 is equivalent to the decimal product 75 of the decimal equivalents 5, 5, and 3 of the binary strings.

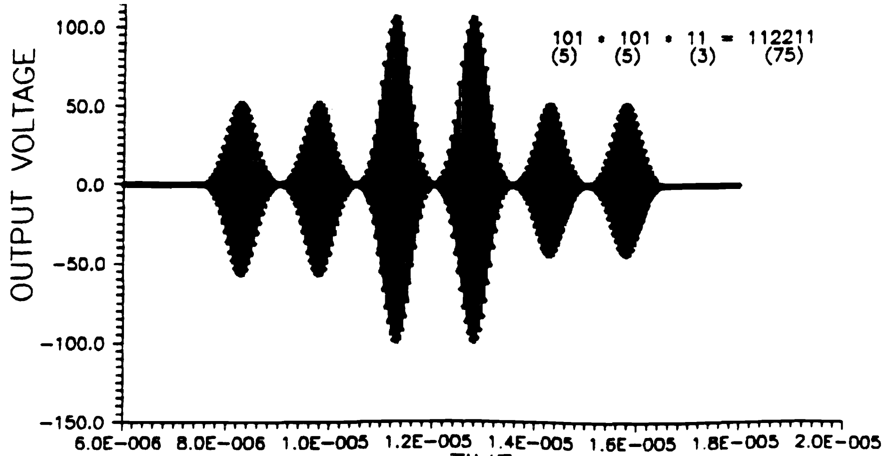


FIG.5.3 MIXED BINARY MULTIPLICATION BY USING PHOTON MEMORY ECHOES. V1:V2:V3=2:2:2.

6. CONCLUDING REMARKS:

Although there are different kinds of nonlinear echoes existing in various physical systems, the photon echo phenomenon is the most attractive echo effect at present. By means of SPICE simulations using equivalent resonators ensembles, we have investigated the characteristics of the photon echo. The triple product formalism of electronic holography, involving correlation and convolution, has been tested for the storage and recall of arbitrary signals and also data bit streams in both time-inverted and nontime-inverted modes by developing implicit nonlinear circuit models in the memory echo domain. Such long-term multiple bit storage and recall are in good agreement with photon echo experiments reported. Furthermore, we have simulated a few specific optical data processing applications in which the mixed binary multiplication of two or more binary bit strings has been achieved. This optical data processing application corresponds well with experiments using spatial image processing in backward-stimulated photon echoes (BSPE), a phenomenon which has been reported recently.

By using the photon echo effect, the optical implementation of neural models may also be developed; high-speed image pattern recognition may be performed; and 1.6-k bit data storage in a time- and frequency-domain hybrid optical memory, in which 16-bit temporal data were stored by accumulated-photon-echo bit by bit storage at 103 frequency addresses, has also been demonstrated. It is conjectured that all of these may be demonstrated by using the parametric model in future research. In addition, we may extend the performance of mixed binary multiplication into the dynamic echo domain. Thus, it has been shown that we may obtain fairly reliable insight into nonlinear optical storage and recall phenomena using SPICE simulations via relatively simple electronic circuits models.

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