Low-noise delays from dynamic Brillouin gratings based on perfect Golomb coding of pump waves

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A method for long variable all-optical delay is proposed and simulated, based on reflections from localized and stationary dynamic Brillouin gratings (DBGs). Inspired by radar methods, the DBGs are inscribed by two pumps that are comodulated by perfect Golomb codes, which reduce the off-peak reflectivity. Compared with random bit sequence coding, Golomb codes improve the optical signal-to-noise ratio (OSNR) of delayed waveforms by an order of magnitude. Simulations suggest a delay of 5 Gb/s data by 9 ns, or 45 bit durations, with an OSNR of 13 dB.

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Stimulated Brillouin scattering (SBS) is a nonlinear interaction between two counterpropagating optical waves that are detuned in frequency by the Brillouin frequency shift Ω_B of an optical medium [1]. The interference between the two optical fields gives rise to a traveling acoustic wave through the mechanism of electrostriction. The acoustic wave, in turn, is accompanied by a so-called dynamic Brillouin grating (DBG) of refractive index variations due to the photoelastic effect [1]. As their name suggests, DBGs can be switched on and off, modified, and moved along a length of fiber by control of the optical waves.

The generation of DBGs along polarization maintaining (PM) fibers has drawn much interest in recent years [2–10]. In these setups, two counterpropagating pump waves, detuned in frequency by Ω_B, are copolarized along one principal axis of the PM fiber. The pumps introduce a DBG, which can be interrogated by a third probe wave polarized along the orthogonal principal axis [2]. Due to the large birefringence of PM fibers, the frequency of the probe wave must be detuned from those of the pumps, typically by a few tens of gigahertz. The probe is back-reflected by the DBG into a fourth wave, which can be measured to monitor the entire process. The use of a third and fourth frequency improves the optical signal-to-noise ratio (OSNR) of the DBG measurements.

DBGs over PM fibers provide a promising sensing platform, as both Ω_B and the fiber birefringence vary with strain and temperature [3–5]. Cascaded DBGs were used in microwave photonic filters [6]. DBGs can also represent movable mirrors for the variable all-optical delay of interrogating probe waves [7–9]. The effective delay of broadband waveforms requires that the DBGs be spatially confined: centimeter-scale gratings are necessary to accommodate Gb/s data. In addition, the magnitude of the index variations must be temporally stable.

Previous works had demonstrated variable delays using DBGs written by pulsed pump waves [7]. However, the inscription of short gratings was restricted by the relatively long acoustic lifetime of $\tau \sim 5$ ns, which corresponds to meter-scale spatial extent [1,7]. Furthermore, pulsed DBGs are inherently transient and must be refreshed periodically [7]. Localized and stationary DBGs were introduced through synchronized frequency modulation of two continuous pump waves, nominally detuned in frequency by Ω_B [8]. Due to the modulation, the frequency difference between the two counterpropagating waves remained stationary at particular fiber locations only, known as correlation peaks, whereas the frequency difference elsewhere was oscillating [11]. In another previous demonstration, a strain gradient was introduced along the PM fiber in order to achieve localization [9].

In recent works, the generation of stationary and localized DBGs was proposed using phase modulation of two continuous pump waves by the photodetected output of a chaotic laser [12], or by a common pseudorandom bit sequence (PRBS) [13]. The magnitude of the DBG is closely related to a windowed autocorrelation of the modulating waveform [12,13]. PRBS coding provides centimeter-long correlation peaks with arbitrary separation [13]. Using this method, 500 ps long periodic pulses were delayed by 770 ns [13], and distributed sensing with cm resolution has been achieved [14]. However, the SNR of the delayed probe waves was fundamentally restricted by the accumulative reflections from residual off-peak DBGs, which correspond to autocorrelation sidelobes [12,13]. Although such gratings vanish on average, their instantaneous magnitude is nonzero and temporally varying. Such "coding noise" degrades the OSNR of the delayed probe wave to unacceptable levels, unless the delay is restricted to a fraction of τ [13]. This limitation can be overcome whenever averaging over repetitious patterns is permitted such as in distributed sensing [14]. Then again, PRBS-coded DBGs remain inapplicable to the delay of one-time signals such as communication data.

In this work, we explore the application of specially designed sequences, proposed initially for radar applications, to the modulation of the pump waves in DBGs over PM fibers. In particular, we employ *perfect Golomb codes* [15], which are characterized by zero sidelobes of the cyclic auto-correlation function. We find through analysis and extensive simulation that the use of Golomb codes instead of PRBS can increase the delay, subject to a given OSNR limitation, by an order of magnitude. Performance is limited by residual nonzero sidelobes, which stem for the windowing that is associated with the DBG representation of the autocorrelation (see in detail below). Simulations suggest the variable delay of 5 Gb/s data by 9 ns with an OSNR of 20.

Let us represent the optical fields of the two pumps as $E_{1,2}(t,z)$, respectively, where t denotes time and z denotes location along a PM fiber of length L. Pump E_1 enters the fiber at $z=0$ and propagates along the positive z direction, whereas pump E_2 propagates from $z=L$ in the negative z direction. The optical frequencies of the two pump waves, $\omega_{1,2}$, are separated by Ω_B. The complex envelopes of the two waves are denoted by $A_{1,2}(t,z)$, so that:

$$E_{1,2}(t,z)=A_{1,2}(t,z)\exp(j\omega_{1,2}t)+\text{c.c.} \tag{1}$$

Suppose that both pump waves are modulated by a common sequence c_n with symbol duration T:

$$\begin{aligned}A_1(t,0)&=A_2(t,L)\\&=A_0\left\{\sum_n c_n\,\text{rect}[(t-nT)/T]\right\}\equiv A(t).\end{aligned} \tag{2}$$

In Eq. (2) c_n is a sequence of unity magnitude and arbitrary phase, rect(ξ) equals 1 for $|\xi|<0.5$ and zero elsewhere, and A_0 denotes the magnitude of both pump waves. It has been shown [1,12,13] that the amplitude $Q(t,z)$ of the acoustic density perturbation is of the form:

$$\begin{aligned}Q(t,z)=jg_1\int_0^t&\exp[-(t-t')/2\tau]\\&\times A(t'-z/v_g)A^*[t'-z/v_g-\theta(z)]\mathrm{d}t',\end{aligned} \tag{3}$$

where the position-dependent offset $\theta(z)$ is defined as $\theta(z)\equiv(2z-L)/v_g$, v_g is the group velocity of the fiber, and g_1 is an electrostrictive parameter [1]. Substituting Eq. (2) into Eq. (3) and discretizing the fiber into $\Delta z=1/2v_gT$ long bins provides the following approximation:

$$\begin{aligned}Q(t,z)&\approx jg_1|A_0|^2T\sum_{n=-\infty}^{n_0(t,z)-1}\exp\left[\frac{(n-n_0)T}{2\tau}\right]c_nc^*_{n-l_z}\\&=jg_1|A_0|^2T\tilde{R}_{N_0}(l_z).\end{aligned} \tag{4}$$

In Eq. (4), the following variables were introduced: l_z is the normalized, position-dependent lag between the sequences: $l_z\equiv\text{round}(\theta(z)/T)$ and $n_0(t,z)$ is the bit appearing in pump A_1 at position z and time t: $n_0\equiv\text{round}[(t-z/v_g)/T]$. Last, $\tilde{R}_{N_0}(l_z)$ is an exponentially windowed autocorrelation function with a memory of $N_0\equiv\text{round}(2\tau/T)$ bits:

$$\tilde{R}_{N_0}(l_z)\equiv\sum_{n=-\infty}^{n_0(t,z)-1}\exp[-(n_0-n)/N_0]c_nc^*_{n-l_z}. \tag{5}$$

Following the initial buildup ($t\gg\tau$), a correlation peak of constant magnitude $Q(t,z)\approx 2jg_1|A_0|^2\tau$ is established where $l_z=0$, with a spatial extent of Δz [12,13]. Reflections from the DBG corresponding to the correlation peak represent the intended signal, whereas reflections from all off-peak DBGs contribute noise. Note that reflected power scales with $|Q|^2$ [1]. The OSNR can be estimated by summing over all $l_z\neq 0$ positions in Eq. (4):

$$\text{OSNR}=\frac{N_0^2}{\left(\sum_{l_z\neq0}\tilde{R}_{N_0}(l)\right)^2}. \tag{6}$$

When c_n is a simple PRBS code, $\tilde{R}_{N_0}(l_z\neq0)$ is a random variable with zero mean and variance of $(1/2)N_0$. Moreover, we assume that for every $l\neq k$, $\tilde{R}_{N_0}(l)$, and $\tilde{R}_{N_0}(k)$ are statistically independent. Given these considerations, the expectation value of the OSNR for reflections from a PRBS-coded DBG is [13]:

$$\begin{aligned}\overline{\text{OSNR}}&=\frac{N_0^2}{\sum_{l_z\neq0}E\left\{\left[\tilde{R}_{N_0}\left(l_z\right)\right]^2\right\}}\\&=\frac{N_0^2}{\sum_{l_z\neq0}\frac{1}{2}N_0}\approx\frac{2\tau v_g}{L}=\frac{4\tau}{T_D}.\end{aligned} \tag{7}$$

In Eq. (7), the maximal round-trip delay variation of reflected probe waves $T_D\equiv 2L/v_g$ is introduced. The OSNR does not comply with telecommunication standards unless T_D is below 1 ns. In order to improve the OSNR, $\tilde{R}_{N_0}(l_z\neq0)$ must be reduced. Fortunately, related problems had been addressed in radar theory. For example, Golomb designed a category of so-called *prefect codes*, having the following useful properties [15]: let a_n denote a perfect Golomb code, repeating with a period of N bits. Its cyclic auto-correlation,

$$R_N(l)\equiv\sum_{n=n_0-N}^{n_o}a_na^*_{n-l} \tag{8}$$

is exactly zero for all $l\neq0$, n_0 [15]. We propose to modulate the pump waves with Golomb codes for the inscription of DBGs over PM fibers. Since $\tilde{R}_{N_0}$ represents an exponentially windowed autocorrelation which is not identical to R_N, we do not expect the off-peak DBGs to vanish entirely. Nevertheless, it is anticipated that Golomb codes would improve the OSNR of delayed probe waves, provided that $N\approx N_0$. Next, this hypothesis is examined through intensive numerical simulations.

Numerical simulations were carried out in two stages. First, the acoustic field magnitude $Q(t,z)$ was calculated through direct integration of the nonlinear coupled SBS equations [1]. The modulation of the two pump waves by different sequences provided the boundary conditions [13]. The following parameters were used: $\tau=5.3$ ns, $L=0.9$ m ($T_D=9$ ns), and $T=100$ ps ($N_0=106$). Figure 1 shows the simulated $Q(t,z)$ with PRBS pump modulation (top left panel), and when a 63 bits-long Golomb code was used instead (top right). The phases of elements $n=\{1\,2\,3\,4\,5\,7\,8\,9\,10\,13\,14\,15\,17\,19\,20\,25\,27\,28\,29\,33\,34\,36\,37\,39\,42\,46\,49\,50\,53\,55\,57\}$ in the Golomb code

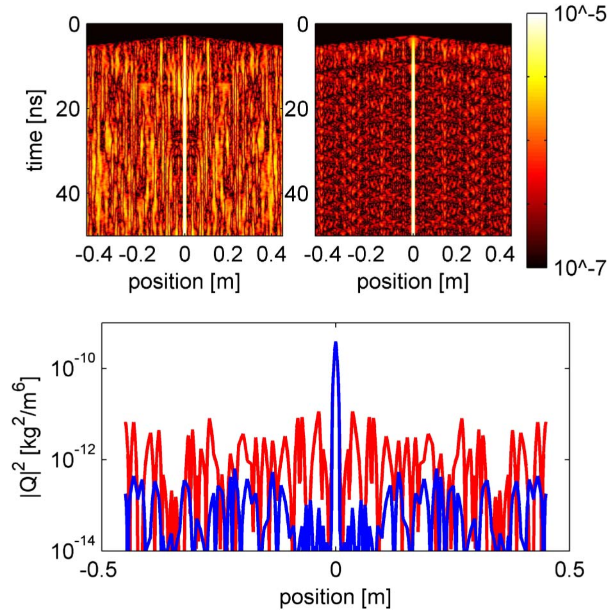

Fig. 1. (Color online) Top: simulated acoustic field magnitude $|Q(t,z)|$ for DBGs written by PRBS coded pumps (left), and by pumps modulated with a perfect Golomb code ($N = 63$, right). The coding symbol duration was 100 ps in both simulations. Bottom: simulated $|Q(t = 10\tau, z)|^2$ for PRBS (red) and Golomb (blue) pumps coding.

equal acos(−62/64), whereas the phases of all other elements are set to zero [15]. While both modulation schemes provide a stationary and localized correlation peak at the fiber center, the off-peak acoustic field is much weaker when Golomb codes are used, as expected (Fig. 1, bottom).

In the second simulation step, the DBGs corresponding to $Q(t,z)$ were interrogated by probe waves, modulated by binary phase-shift-keying PRBS data at 5 Gb/s. The interrogation does not affect $Q(t,z)$ as long as the probe power is considerably weaker than that of the pumps [10]. The intended signal power was calculated by artificially nullifying all off-peak DBGs, and the noise power was calculated by removing the correlation peak. The OSNR for PRBS pump modulation was only 2.1, in agreement with the prediction of 2.35 in Eq. (7). In contrast, the Golomb code improved the OSNR by an order of magnitude to 20.5. The OSNR values were averaged over multiple realizations. The results suggest that DBGs over PM fibers could provide a delay-bandwidth product of 45 while retaining sufficient signal integrity.

Last, Fig. 2 shows the eye diagrams of delayed 5 Gb/s PSK waveforms, reflected from DBGs induced by PRBS-coded pumps (top) and Golomb-coded pumps (bottom). Golomb coding leads to an open eye diagram whereas PRBS coding results in a nearly closed diagram.

In conclusion, formalism was provided for the OSNR of probe waves reflected from a DBG, subject to arbitrary sequence coding of the two pump waves. A high OSNR requires effective sidelobe suppression in the exponentially windowed autocorrelation of the modulating code. In analogy with radar systems, perfect Golomb codes were proposed for inducing stationary and localized DBGs with reduced off-peak reflectivity. Numerical simulations predict the delay of 5 Gb/s digital data by 9 ns

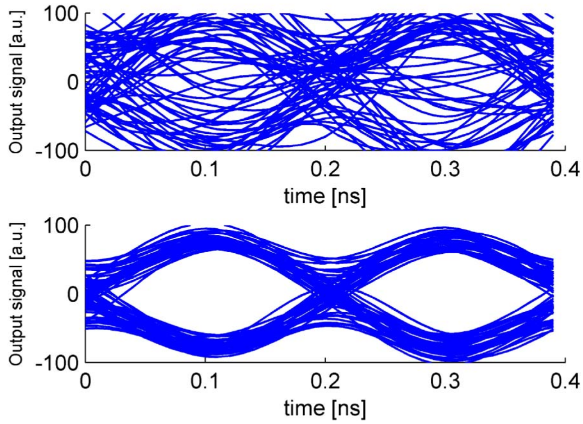

Fig. 2. (Color online) Simulated eye diagrams of 5 Gb/s PSK data streams, delayed by DBGs induced along a 90 cm long PM fiber. Top: PRBS-coded pumps. Bottom: pumps modulated by a perfect Golomb code ($N = 63$). The coding symbol duration was 100 ps in both simulations.

with an OSNR of 13 dB. This delay is an order of magnitude longer than that of DBGs written with PRBS-modulated pumps, and two orders of magnitude longer than that of optimized SBS-based "slow light" setups [16]. The method is scalable to longer delays with the use of longer Golomb codes, at the expense of a lower OSNR. The results demonstrate the potential of carrying over radar-inspired techniques to the field of all-optical signal processing [14]. Future work will be dedicated to a corresponding experimental demonstration.

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