Design of a tunable time-delay element using multiple gain lines for increased fractional delay with high data fidelity

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A slow-light medium based on multiple, closely spaced gain lines is studied. The spacings and relative strengths of the gain lines are optimized by using the criteria of gain penalty and eye-opening penalty to maximize the fractional delay defined in terms of the best decision time for random pulse trains. Both numerical calculations and experiments show that an optimal design of a triple-gain-line medium can achieve a maximal fractional delay about twice that which can be obtained with a single-gain-line medium, at three times higher modulation bandwidth, while high data fidelity is still maintained. © 2007 Optical Society of America

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A practical way for realizing slow light [1] is to use the strong dispersion near a resonance gain feature of a medium, which has promising applications such as all-optical buffering and data resynchronization. This procedure allows for continuous modification of the group index by changing the magnitude of the gain coefficient. In practice, the maximum achievable fractional delay [2] (also known as the delay–bandwidth product [3]) $\overline{\Delta T}_{\max} \equiv \Delta T_{\max} 2\pi \Delta \nu$ is often considered to be a primary figure of merit of a slow-light device; here $\Delta T_{\max}$ is the maximum achievable absolute delay, and $\Delta \nu$ is the signal bandwidth. However, because both the gain coefficient and group index n_g vary significantly in the vicinity of a resonance gain line, $\overline{\Delta T}_{\max}$ is often limited by pulse distortion [4,5], especially when $\Delta \nu$ becomes comparable with or larger than the spectral width of the gain feature.

It has recently been shown that $\overline{\Delta T}_{\max}$ can be increased by using two [6] or more [7–10] gain lines or flattened gain profiles [11,12]. In these papers, delay was usually defined in terms of the peak position of a single Gaussian pulse, and the influence of such modified gain profiles on the system performance has not been studied in detail. In a real system, however, data packets comprise varying sequences of "0" and "1" bits in designated time slots, and the peak positions of individual pulses often experience a pattern-dependent delay [4] due to intersymbol interference (ISI) [13] etc. Thus, a better and more practical way to determine the delay of a data packet through a slow-light medium is to define it in terms of the best decision time (BDT) t_{opt} in the eye diagram when the highest data fidelity [i.e., lowest bit error rate (BER)] is achieved. Note that the eye diagram is also most open at t_{opt}; this thought can be quantified by using the eye-opening metric $\mathcal{E} \equiv \max(P_{1,\min}(t) - P_{0,\max}(t))$,

where $P_{1,\min}(t)$ and $P_{0,\max}(t)$ are the lowest and highest normalized power among all "1" and "0" bits at time t within the time slot, respectively. Consequently, the BDT delay of a data packet can be determined by comparing the values of t_{opt} for propagation through the slow-light medium and through a reference medium. In the rest of this Letter, fractional delay will be based on this definition.

The complex refractive index for a medium with multiple Lorentzian gain lines can be written as

$$\tilde{n}(\nu) = 1 + \sum_j \frac{cg_j}{4\pi\nu_0} \frac{\gamma}{\nu - \nu_0 - \delta_j + i\gamma}, \qquad (1)$$

where ν_0 is the center frequency of the entire gain feature; g_j and δ_j are the peak gain coefficient and the shift of the resonance center from ν_0 of the jth gain line, respectively; c is the speed of light in vacuum; and γ is the half-width at half-maximum linewidth of each gain line. To keep $\tilde{n}(\nu)$ even–symmetric about ν_0, we require that $g_j = g_{-j}$ and $\delta_j = -\delta_{-j}$. Since $\overline{\Delta T}_{\max}$ varies for data packets with different bandwidths, the parameters δ_j and g_j are optimized for each $\Delta \nu$ individually by using two criteria. The first criterion is that the maximum continuous wave (CW) exponential intensity gain within the bandwidth be less than a realistic value of 7 (~30 dB),

$$\max\{2k_0 \mathfrak{I}[\tilde{n}(\nu)]L\} < 7, \quad |\nu - \nu_0| < \Delta\nu, \qquad (2)$$

where $\mathfrak{I}[\ ]$ represents the imaginary part, and L is the length of the medium. The second criterion is that the eye-opening penalty [14] (EOP) be less than 1.87 dB,

$$EOP \equiv -10 \log(\mathcal{E}_{out}/\mathcal{E}_{in}) < 1.87 \text{ dB}, \qquad (3)$$

where $\mathcal{E}_{in/out}$ is the eye opening at input and output of the slow-light device. Note that, for a system that has a detector-limited signal-to-noise ratio (SNR) of 35 dB, an EOP of 1.87 dB indicates [14] that with an ideal input the output BER is still less than 10^{-12}. Note also that the EOP is closely related [14] to the Q-factor penalty [4], and both merits can be cascaded through various elements to describe the overall system performance.

In both numerical calculation and experiment, 128 bit random data trains with return-to-zero modulation are used. A logical "1" bit is represented by a pulse with an input amplitude shape of $A(t) = \exp(-t^2/\tau^2)$ for $|t| < 2\tau$, where τ is the time constant and $T_{slot} = 4\tau$ is the length of the time slot. A logical "0" bit is represented by the absence of such a pulse in the time slot. The bandwidth $\Delta\nu$ is related to T_{slot} by $\Delta\nu = 1/2T_{slot}$.

The experiment (Fig. 1) is performed using 2 km of small-core fiber (SCF) in which the gain features are produced by the stimulated Brillouin scattering (SBS) effect [15,16]. The SBS gain linewidth γ in the SCF is measured to be 25 MHz. Multiple gain lines are created by amplitude modulating the pump light with a Mach–Zehnder modulator (MZM) [7,8]. For example, with a driving voltage of the MZM in the form $V_{MZM} = (-V_\pi + rV_1/2 + V_1 \cos 2\pi\delta t)$, where V_π is the half-wave voltage of the MZM, the pump field after modulation has the form $E_{p,out} = E_{p,in}V_1/(2V_\pi)(r + e^{i2\pi\delta t} + e^{-i2\pi\delta t})$, where $E_{p,in}$ is the input pump amplitude. After amplification by an erbium-doped fiber amplifier (EDFA), such a pump field creates a triple-gain-line (TGL) feature near its Stokes shift frequency with half separation δ and peak ratio $r = g_0/g_1$ between the center and side gain lines. Once the shape of the gain profile is achieved, its magnitude can be tuned continuously by changing the amplification of the EDFA.

Figures 2(a) and 2(b) show $\overline{\Delta T}_{max}$ and corresponding EOP, respectively, as functions of the normalized bandwidth for the single-gain-line (SGL), double-gain-line (DGL), and TGL media. For a slow-light medium based on a fixed number of gain lines, one sees that there is a peak bandwidth $\Delta\nu_{peak}$ at which a
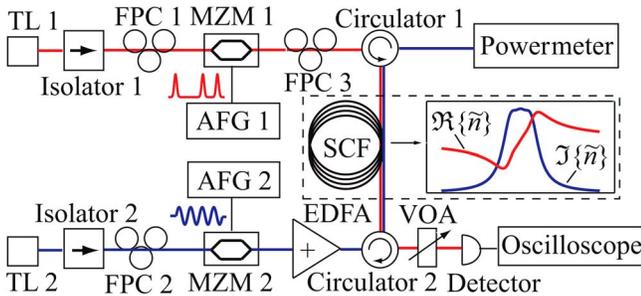

Fig. 1. (Color online) Schematic diagram of a SBS-based tunable delay line. TL, tunable laser; FPC, fiber polarization controller; AFG, arbitrary function generator; VOA, variable optical attenuator. The inset on the right shows a typical profile of $\tilde{n}$ for a TGL medium.
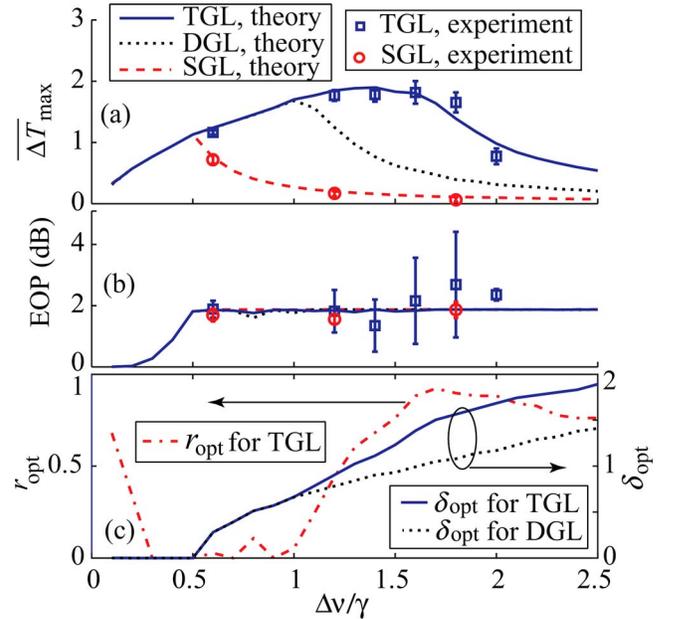

Fig. 2. (Color online) (a) Maximum achievable fractional delay $\overline{\Delta T}_{max}$; (b) corresponding EOP; and (c) optimum values of the half separation δ_{opt} and peak ratio r_{opt} as functions of normalized bandwidth for the SGL, DGL, and TGL media, respectively.

largest $\overline{\Delta T}_{max}$ can be achieved. For bandwidths less or larger than $\Delta\nu_{peak}$, $\overline{\Delta T}_{max}$ is limited mainly by the maximum gain or the EOP criterion, respectively. As the number of lines incorporated into the gain feature increases, more degrees of freedom are available to optimize the gain and refractive index profile and thus minimize the distortion and ISI. Thus, a larger $\overline{\Delta T}_{max}$ at a larger $\Delta\nu_{peak}$ can be achieved with an optimum design of relative spacing and peak ratio among the gain lines. As one sees from Fig. 2(a), the largest $\overline{\Delta T}_{max}$ for a TGL medium is around 1.9, which is about twice the largest value that can be obtained with a SGL medium. Moreover, its peak bandwidth $\Delta\nu_{peak}$ is about three times that for a SGL medium. Note that for both SGL and TGL media the maximum CW gain within the bandwidth reaches our assumed limit of 7 in order to achieve the largest $\overline{\Delta T}_{max}$ for each case.

Figure 3 shows the eye diagrams of the input and output in a theoretical noise-free situation [Figs. 3(a) and 3(b)] and in the experiment Figs. [3(c) and 3(d)] for the optimum design of a TGL medium at $\Delta\nu = 1.4\gamma$ with $\overline{\Delta T} \approx 1.9$. The optimum parameters are $\delta = 1.1\gamma$ and $r = 0.68$, and the peak gain of the data train in the time domain is about 24 dB. One sees that the theoretical prediction and experimental results agree well and that ISI, not noise, is the main source of the eye closure and the associated reduction in data fidelity. Under such circumstances, one also sees that the largest deviation among the peak positions of different "1" bits is almost half a bit slot. Thus it is indeed ambiguous and inaccurate to define the delay in terms of the peak position of any individual "1" bit.

For a given bandwidth $\Delta\nu$, once the optimum gain profile is obtained (e.g., by using the parameters plot-

Theoretical noiseless case
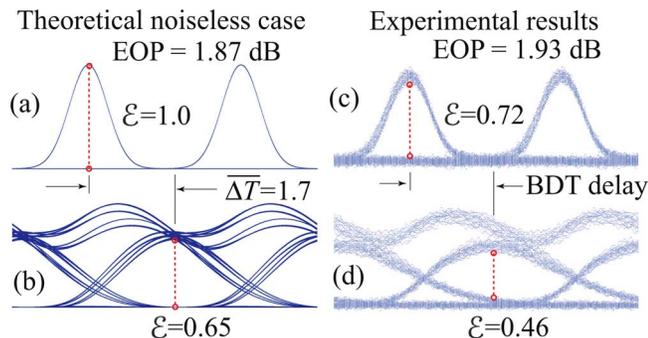EOP = 1.87 dB

Experimental results
EOP = 1.93 dB

Fig. 3.   (Color online) The eye diagram of (a) a theoretical noiseless input, (b) a theoretical noiseless output, (c) the actual input in the experiment, and (d) the actual output in the experiment for the optimum design of a TGL medium with $\overline{\Delta T} \approx 1.9$ at $\Delta \nu = 1.4\gamma$. The dotted lines indicate the magnitude of the eye opening $\mathcal{E}$ of each case.

ted in Fig. 2(c) for a TGL medium), tunable delay can be achieved by changing the magnitude of the gain profile. Figure 4 shows the simulated results of $\overline{\Delta T}$ and EOP as the magnitude of the gain profile (normalized by the optimum value to achieve $\overline{\Delta T}_{max}$) increases for the optimum designs of TGL media for various bandwidths. One sees that the delay typically increases linearly first as the gain increases from zero. This is because at small gain the distortion is small so that the BDT delay is consistent with the peak delay of the "1" pulses. As the gain becomes larger, the ISI becomes larger and t_{opt} starts to deviate from the peak positions of the "1" pulses, and therefore $\overline{\Delta T}$ is no longer strictly linearly proportional to gain afterwards but increases faster as gain increases. Meanwhile, the EOP also increases slowly at first [see Fig. 4(b)] when the distortion is small. For $\Delta \nu = 1.4\gamma$ [when the overall largest $\overline{\Delta T}_{max}$ is achieved; see the solid curve in Fig. 4(b)], in particular, EOP is negligible for a relative gain magnitude less than 0.3. This shows that a good design of a
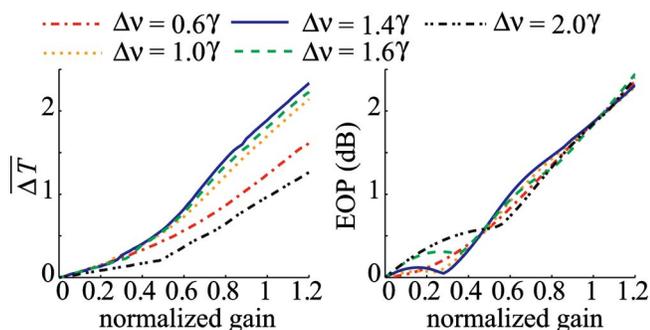

Fig. 4.   (Color online) (a) Simulated results of fractional delay $\overline{\Delta T}$ and (b) EOP as functions of gain (normalized by the gain required for achieving $\overline{\Delta T}_{max}$) for optimum designs of a triple-gain medium at various bandwidths.

multiple-gain-line medium can actually increase the delay with negligible loss in data fidelity.

In summary, a slow-light medium based on multiple, closely spaced gain lines has been studied by using the definition of best-decision-time delay and the metrics of maximum gain and eye-opening penalty. The theoretical predictions have been demonstrated with a tunable delay line based on the SBS effect in fiber. It has been shown that the maximum achievable fractional delay can almost be doubled at three times larger modulation bandwidth for an optimized triple-gain-line medium as compared with a single-gain-line medium, while high data fidelity is still maintained. This scheme is applicable in a straightforward way to much higher data rate by using techniques that increase the effective linewidth of each gain line [12,17] or that increase the number of gain lines [9,10].

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