Efficient Time-Domain Demultiplexing with Separate Signal and Control Wavelengths in an AlGaAs Nonlinear Directional Coupler

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Abstract—Efficient time-division demultiplexing using two different wavelengths, one for the signal and one for the control beam, has been implemented in an AlGaAs nonlinear directional coupler at 1550 nm. This all-optical demultiplexer makes use of cross-phase modulation and walk-off between the two wavelengths to give high contrast at both low and high powers and to eliminate the pulse break-up. Additionally, ultrafast wavelength shifting has been observed.

I. INTRODUCTION

The usable transmission bandwidth of optical fiber communication networks is currently limited by the ability to modulate signals at very high repetition rates. It has been suggested that this electronic limitation could be eliminated using all-optical modulation and switching techniques [1]–[3]. This philosophy has been demonstrated using a variety of approaches in fibers and semiconductor waveguides [1]–[32]. Our approach to such ultrafast, low-power and low-energy all-optical switching has been based on semiconductors operated at photon energy below half the band gap [15]–[18], [21], [32]. To date a number of different switching device configurations have been implemented, namely: the nonlinear directional coupler (NLDC), the nonlinear X-Junction, and the nonlinear Mach–Zehnder interferometer [15]–[18]. This particular combination of material and wavelength has also proved ideal for demonstrating a range of effects that require a Kerr-like nonlinearity—for example, spatial solitons and soliton steering have been observed [33], [34].

One particular application of all-optical switches is to demultiplex data at high speeds, i.e., to switch out one or a series of data bits from a continuous high-bit-rate data stream. In all-optical systems this requires the overlap in time of a control beam with the signal bit to be rerouted [21]–[31]. Using cross-phase modulation, the polarization, frequency, or waveguide can be changed for a data bit and hence any one of these properties can be used to isolate and reroute the desired data bit. These features have been used very successfully in fibers for demultiplexing both temporal soliton and nonsoliton signals [1]–[3], [24]–[31]. More recently, semiconductor amplifiers used in loop mirrors have been used to reroute data bits during the decay time of the induced excitation (index change), typically tens of picoseconds [22], [23]. Using a NLDC based on AlGaAs with photon energies below one half bandgap, we have reported a preliminary demonstration of an ultrafast integrated all-optical demultiplexer [21]. One of the advantages of using integrated formats is that the latency time is very short compared to similar devices that require long lengths of optical fiber [21]–[23].

Our initial demultiplexing experiment, reported in [21] was based on a one coupling length-long directional coupler (DC). In such a device two parallel waveguides in close proximity are coupled by their evanescent fields. At low intensity, i.e., in the linear case, the light will couple from the BAR state or input waveguide to the CROSS state or the adjacent waveguide. Hence, the designation as a one coupling length (Lc) long directional coupler. However, at high input intensity the nonlinearity will detune the coupler and all the light will remain in the input waveguide or BAR state. The demultiplexing was based on the cross phase modulation imposed on the weak, TM polarized signal, by the strong TE polarized control pulse. The major disadvantage of this method of implementing an all-optical demultiplexer is the associated pulse break-up, whereby the high intensity portion of the control beam has sufficient intensity to completely detune the coupler, while the low intensity wings of the control pulse have insufficient intensity to switch the coupler [8], [9], [15], [16]. The result is poor energy contrast between the low and high input intensity states. Our goal here is to avoid pulse break-up and hence to obtain the maximum contrast between the on and off state of the demultiplexer; i.e., the maximum difference in the signal output between the presence and the absence of the control beam.

In our previous implementation of an all-optical demultiplexer we identified some improvements that could be made. Complete details can be found in [21]. Here we only present a brief summary. As already mentioned we previously used two different polarizations for the signal and control, and the pulse widths were identical. From Fig. 2 of [21] we note that the low-power switching fraction does not start from 0% for the bar state (100% for the cross state). This has the
effect of reducing the possible contrast between the on and off states. This problem was caused by the fact that we had two different polarizations which, in turn, had two different coupling lengths. The coupler had a length equivalent to 1 Lc for the TE mode (control) and 1.4 Lc for the TM polarization (signal). The dependence of coupling length on polarization can be eliminated by using a signal and pump with the same polarization and slightly different wavelengths. Hence, in order to have a one coupling length-long device for both the control and signal and to be able to differentiate the control and signal pulses at the output of the demultiplexer, we need to use two different wavelengths.

A second problem identified was that the switching fraction at high control intensity did not reach 100% in the bar state. This was caused by pulse break-up. The obvious solution of using a temporal soliton for switching is, unfortunately, not feasible with AlGaAs at half the band gap since both the group velocity dispersion ($\beta_2$) and the nonlinearity are positive [36], [37]. Another option is to use a long control pulse to switch a shorter signal pulse. The signal would switch completely if all of its time envelope fell beneath the central, almost constant, part of the control pulse as shown schematically in Fig. 1(a). Because different wavelengths have different velocities, a variant on this option is to “walk” the signal pulse through the control pulse so that it accumulates a constant phase shift over its envelope in a fashion similar to that of a soliton Fig. 1(b) (for example, [4], [25]).

Both problems discussed above were solved by switching a short, weak signal (150 fs) at 1640 nm with a longer, stronger control pulse (600–800 fs) at 1550 nm. In this paper we report the first demonstration of an integrated optics demultiplexer in which the signal and pump have different wavelengths. This represents the practical situation where a local pump source at $\lambda_1$ could be used to demultiplex an incoming signal at $\lambda_2$. We also report a detailed numerical simulation of the device, the results of which are in good agreement with experimental results. In Section II we will present a detailed description of the experimental set-up used to generate two synchronized pulse trains with different wavelengths. A brief description of the nonlinear directional coupler is given in Section III. In Section IV we describe the model used to simulate the two wavelength demultiplexing experiment. Then in Section V we give a comparison between the experimental results and the numerical simulations. Finally, in Section VI we present our conclusions.

II. EXPERIMENTAL SET-UP

The experimental apparatus is shown in Fig. 2. The laser source is a NaCl:OH color center laser, synchronously pumped by a Nd:YAG laser at 76 MHz. The typical output of this laser system is tunable between 1470 and 1740 nm with pulses of 3 to 6 ps duration. The laser was modified by incorporating a coupled cavity to produce 300 to 900 fs pulses tunable between 1500 and 1610 nm.

The control and signal pulse trains were generated in two separate branches of the experiment. The control branch consisted of a 9-m-long optical delay line. The signal branch consists of 5.5 m of dispersion-shifted single-mode optical fiber from Corning (CPC3). Between 30 and 50 mW (at 76 MHz) of average power was coupled into the fiber. Depending on the details of the experiment, the output laser pulse width could be varied from 600 to 800 fs. The wavelength of the laser was close to the zero dispersion of the particular fiber, i.e., 1555 nm. During the pump propagation through the fiber, the pump spectrum broadens due to the effect of self-phase modulation. The Stokes part of the self-modulated spectrum falls into the negative group velocity dispersion region of the fiber. Hence, a soliton-like pulse is formed from the Stokes part of the pump spectrum. Additionally, due to the Raman self-scattering (self-frequency shift) effect, the soliton spectrum moves further to the Stokes spectral region and becomes completely separated from the rest of the pump. The spectrum of the radiation emerging from the fiber is shown in Fig. 3 by the dashed line. Measured spectral bandwidth and pulse width were 20 nm and 150 fs, respectively. The wavelength of the soliton pulse could be varied between 1630 and 1650 nm by changing the average pump power coupled into the fiber. To isolate the background-free soliton-like pulse from the rest of the fiber output spectrum, an interference filter was used. The filter centered around 1670 nm for normal incidence and having a 37-nm bandwidth, was
tilted for optimum transmission of the 1640-nm soliton. The spectrum transmitted through the filter is shown by the solid line in Fig. 3. Comparison of the measured autocorrelation traces of the laser pulses and the soliton pulses with the cross-correlation trace of the laser and the soliton pulses showed that timing jitter between the soliton and the laser pulses was much less than the pulsewidth. Details of this source will be published elsewhere.

The polarization of the light output from the fiber was changed to TE using a polarization rotator in order to match the polarization of the control pulse. Both beams were then combined in the last part of the set-up using a dichroic mirror and coupled together into the input waveguide of the NLDC using an antireflection-coated, 20× microscope objective. The outputs from the NLDC were collected using a 60× microscope objective in order to separate the two output channels for detection by two Ge detectors. We separated the control from the signal by inserting another filter after the NLDC. This filter had a wider bandwidth, 47 nm, centered at 1682 nm, and was adjusted for optimum transmission of the 1640 pulses and minimum transmission of the control pulses.

III. DESCRIPTION OF THE NLDC

The NLDC used here is the same one discussed previously in [15], [16], and [21] so that we will only summarize its properties. The waveguides were grown by molecular beam epitaxy on a GaAs substrate, and consisted of a threelayer structure. A 1.5-μm waveguide layer of Al0.15Ga0.85As was grown on a 4-μm-thick buffer layer of Al0.24Ga0.76As. The buffer layer thickness was designed to avoid power leakage into the higher index GaAs substrate. To have a more symmetric waveguide and to avoid surface scattering center, a 1.5-μm cladding of Al0.24Ga0.76As was grown over the waveguide layer. The cladding layer was then patterned using a combination of photolithography and reactive ion etching with SiCl4, to produce the two parallel 5-μm-wide waveguides spaced by 7 μm, which formed the NLDC. The effective area $A_{\text{eff}}$ of the waveguide was calculated by different techniques to be between 11 and 13 μm², and the nonlinear index of refraction was measured to be $n_2 = 1.1 \times 10^{-13}$ cm²/W [32], [39]–[41]. The total sample length was 2.2 cm with the NLDC's length measured to be 2.14 cm; i.e., the coupling section was preceded by a short single-input waveguide section to ensure that the light was launched only into a single arm of the coupler. The group velocity of the AlGaAs waveguide was measured independently by two different methods to be 1.4 ps²/m (~1100 ps/nm/km) [36], [37]. There was no significant two photon or three absorption in these waveguides, as described in [15], [16], and [42] and the linear loss was measured to be less than 0.5 cm⁻¹.

IV. NUMERICAL SIMULATION

We have numerically simulated the demultiplexing process using a model consisting of four coupled-mode equations; one for each of the signal and control pulses in each waveguide. In doing so, we have assumed that the spectra of the signal and control did not overlap and that we could physically separate them. This assumption will be validated in Figs. 8 and 9. The equations used to describe the evolution of the signal and control fields along the coupler are given by

$$i \frac{dE_{[s,B,C]}(z)}{dz} = -\kappa_s E_{[s,C,B]} + \frac{\beta_2}{2} \frac{d^2 E_{[s,B,C]}(z)}{dz^2} - \frac{n_2 k_0}{A_{\text{eff}}} |E_{[s,B,C]}|^2 E_{[s,B,C]}$$

$$i \frac{dE_{[s,C,B]}(z)}{dz} = -\kappa_s E_{[s,C,B]} + \frac{\beta_2}{2} \frac{d^2 E_{[s,B,C]}(z)}{dz^2} - \frac{2n_2 k_0}{A_{\text{eff}}} |E_{[s,B,C]}|^2 E_{[s,B,C]}$$

where the subscripts $B$ and $C$ represent the BAR and CROSS states (waveguides), $E_s$ is the control field, and $E_d$ is the signal
field. Furthermore, $\kappa_c$ and $\kappa_s$ are the coupling constant for the control and signal, respectively, assumed to be $\kappa_c = 73.4 \text{ m}^{-1}$ and $\kappa_s = 57.5 \text{ m}^{-1}$, and $\beta_2$ is the group velocity dispersion, which is assumed to be identical for both wavelengths. We neglected the third-order dispersion, which resulted in an error of less than 10%. The input field was defined as

$$
E_c = E_0 \sec h(t/T_c) \\
E_s = \sec h((t - t_d)/T_s) \exp(-\Delta \omega (t - t_d)) \\
\Delta \omega = 2\pi c(1/\lambda_0 - 1/\lambda_c)
$$

where $E_0$ has units of $W^{1/2}$, $t_d$ is the time delay between the control and signal at the input, $\Delta \omega$ is the difference in frequency between the control and signal, $T_c$ and $T_s$ are defined as the full-width half-maximum (FWHM) of the pulse divided by 1.763. The FWHM’s were 600 and 150 fs for the control and signal, respectively. The initial fields and equations are an alternative representation of the propagation problem that includes the walk-off term [43]. We chose to use separate equations for the signal and control in each waveguide since we can physically separate them due to their different wavelengths. This representation would have been inappropriate if the two pulses had significant spectral overlap. The propagation was performed numerically using a fast Fourier transform (FFT) beam propagation algorithm. We used 512 points across the time domain for each pulse, and between 300 and 1000 points along the 2.2-cm-long propagation. Care was taken to ensure that there was no loss or gain of energy during the propagation.

Fig. 5. Experimental signal-beam switching fraction into the BAR state versus input intensity for various time delays $t_d$.

V. EXPERIMENTAL AND NUMERICAL RESULTS

Experimentally it is difficult to precisely set the value of $t_d$ in the femtosecond pulse regime. Using trial and error, optimized switching is defined operationally as the experimental results shown in Fig. 4(a). The low-power switching fraction (linear coupling) is approximately 15%. This is significantly better than our previous implementation of an all-optical demultiplexer where the linear switching fraction was 30%. It can clearly be seen that the high-power switching fraction tends to 100%, indicating that pulse break-up was absent. The best match of the simulation to the experiment was obtained for $t_d = 0.75 \text{ ps}$, shown in Fig. 4(b).

The effects of detuning from $t_d = 0$ are shown in Figs. 5 and 6. (Positive detuning means that the control beam enters the NLD first). Fig. 5 shows a series of switching curves taken in steps of 0.33 ps. There is approximately a 1-ps window between +0.66 ps and -0.33 ps, where there is acceptable switching, demonstrating that this type of switching will have some tolerance to timing jitter. Here the control pulse was 630 fs long at 1555 nm, and the signal was centered at 1640 nm with a pulse width shorter than 150 fs (the limit of our autocorrelator). At a detuning of $t_d = \pm 1.0 \text{ ps}$ there is little switching because the two pulses do not interact significantly.

Figure 6 presents numerical results for successive delays spaced by 0.25 ps in order to have a better sampling of the temporal behavior of the demultiplexer. There is, once again, a good qualitative agreement between the numerical and experimental results, although the actual location of the experimental zero delay is hard to define exactly, but must be
between +0.75 and +1.25 ps for the simulation. Hence even the temporal behavior is reproduced within approximately 1 ps in which acceptable switching occurs, in agreement with the experimental results.

It is important to note that because the signal power was kept constant and because there is negligible nonlinear absorption, the switching fraction of the signal could also have been labeled as the output power. Hence, there is a real transfer of energy between the two NLDCs' channels. The power in the BAR state at high input power is significantly higher than the power at low input powers, and vice versa for the CROSS state. This means that a threshold device could easily discriminate between the on and off states of the demultiplexer.

Unfortunately, for technical reasons we were unable to perform autocorrelation on the output pulses to verify that there is indeed no pulse break-up (although the switching fraction close to 100% clearly indicates the absence of pulse break-up). However, the computer simulations have demonstrated that there is little pulse break-up. Shown in Fig. 7 are the normalized control and signal pulses at the input ($Z = 0$).
and the output ($Z = L$) of the NLDC for 300 W peak power or 2.5 GW/cm² peak intensity. The broadening of the control pulse in due to both the strong self-phase modulation and the GVD. In this example the signal enters the coupler with a delay of +1.0 ps and exits with a delay of −0.8 ps with very little broadening. The observed broadening is simply due to the GVD and is not accentuated by the SPM. We have confirmed this explanation by propagating a signal pulse with a (low power) control beam present and the corresponding output of the CROSS state is shown in Fig. 7(b). The broadening of the signal is approximately the same as for the high-power case. An interesting feature is that the output time of the peak has shifted to 1.1 ps. This transit time change is due to the cross-phase modulation, which causes a change in the optical path, the consequence of which will be discussed in more detail below.

The frequency spectra of the control and signal beams are presented in Fig. 8(a); the SPM has considerably broadened the control, which explains the large temporal broadening. However, the signal spectrum does not broaden much but its peak wavelength position changes. Experimentally, we have observed little wavelength shifting and some wavelength broadening for control pulses shorter than 650 fs. However, when pulses longer than 800 fs were used, we observed significant wavelength-shifting as shown in Fig. 9. In this figure the output spectrum of the signal pulse without the control is shown by the short dashed line. The spectrum of the control beam is shown by the long dashed line (note that initially there is little overlap between the signal and control as assumed in the model). Finally, the solid line is the signal in the presence of a control pulse. Some broadening and a wavelength shift of more than 20 nm can be observed. Obviously, at low control intensity no spectral broadening or shift is observed.

The shift occurs when the signal pulse does not pass symmetrically and completely through the control pulse [12], [29], [44]. This effect was most significant for longer control pulses (>800 fs), and was almost absent for all delays with shorter control pulses (<650 fs). As a result, when the probe pulse does not “pass” completely through the longer control pulse, a wavelength shift occurs, due to the asymmetric interaction between the two pulses. To understand this, it is necessary to consider that the instantaneous frequency of a
pulse is related to the derivative of its instantaneous phase. Simply put, when the signal pulse encounters the leading edge of the control pulse it suffers a wavelength shift. This wavelength shift is reversed when the signal encounters the trailing of the control pulse, leading to a symmetric interaction and no net wavelength shift. However, for longer control pulses and for certain delays the interaction is incomplete, which results in a wavelength shift. An example of a signal wavelength shift using a 810 fs control pulse is shown in Fig. 9, which was discussed previously.

Many applications of all-optical switching would benefit considerably from an element with a square switching window. Recent work has concentrated on terahertz all-optical demultiplexers (TOAD’s), which used a resonant nonlinearity, asymmetrically positioned in a fiber loop mirror [23]. The switching window is defined in time by the relative arrival times of the two counter-propagating signal pulses and the control pulse. In the demultiplexing experiment presented here, we can utilize the wavelength shift experienced by the signal by using wavelength filters to differentiate the control from the signal at the output to produce a square switching window in power. Experimental results are presented in Fig. 10. In this example the low-power switching contrast was optimized by adjusting the output wavelength filter. As the power in the control pulse is increased the coupler begins to switch and the transmission increases to \( \sim 100\% \). Further increases in the control power then cause the wavelength of the signal pulse to shift, with the result that the transmission of the filter begins to fall. These initial results on the combined use of a nonlinear switching element and an induced wavelength shift show that it is possible to increase the sharpness of the normalized switching fraction and produce a switching window. Further experiments are required to explore the usefulness of this effect.

VI. CONCLUSION

In conclusion, we have presented the first experimental demonstration of an integrated optics all-optical demultiplexer, where the signal and control pulses have different wavelengths. This type of demultiplexing operation corresponds to the situation where a local pump source is used to modulate or switch the data present on an incoming signal channel. The demonstration also shows that when a control pulse with a longer duration than the corresponding signal pulse is used the energy contrast of the resulting switching fraction increases to \( \sim 100\% \). This implies that the detrimental effects of pulse break-up have been eliminated.

Our results also demonstrate the existence of a time window where efficient switching can still be achieved, implying that the use of different pulse lengths introduces a tolerance to timing jitter. In the particular example reported here the window was \( \sim 1 \) ps in duration. By proper choice of the experimental parameters the width of this window can be varied to a certain extent. Such a tolerance to timing would be useful in real system applications. For example, in a soliton communications system Gordon–Haus jitter gives rise to variations in the arrival time of the signal pulses. The use of an all-optical element that has a resilience to timing errors would allow the possibility of all-optical re-timing.

The use of an integrated format for implementing all-optical functions has several added advantages over corresponding devices in fiber. The latency time, or transit time, of the element is reduced to a minimum, devices are less sensitive to environmental effects such as temperature and pressure, and the total size is minimized.

REFERENCES


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