The Distributed Bragg Pulse Shaper: Demonstration and Model

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Abstract—The distributed Bragg pulse shaper (DBPS) is a series of electrically switchable Bragg mirrors on a semiconductor waveguide. The DBPS encodes data packets using parallel electrical signals to set the states of the Bragg mirrors. A broad-band source pulse then probes the device to generate a high bandwidth serial wavepacket from the train of partially reflecting mirrors. This paper describes a DBPS constructed in AlGaAs. Using this device and a mode-locked Ti:sapphire laser, we create a 4-bit packet with 0.37 Tb/s burst bit rate and we demonstrate for the first time that bits in the wavepacket can be switched by electrical modulation of individual Bragg segments. We also describe a model collaborating the observed data.

Index Terms—Integrated optics, optical communication, optical pulse shaping, optical transmitters, ultrafast optics.

I. INTRODUCTION

OPTICAL data transmission at bandwidths approaching or exceeding a terahertz can be achieved by wavelength, coherence, or time-domain multiplexing [1]–[4]. Data are encoded for these systems using multiple source arrays or on multichannel filtering of a single broad-band source. While several vendors now offer commercial WDM systems at several hundred Gb/s, the less developed single source approach has advantages in simplicity and efficiency of coupling to fiber systems, and ultimately, cost. This paper describes a compact multichannel filter for single broad-band source modulation that converts parallel electrical signals to a serial optical signal. The device consists of a series of partially reflecting Bragg mirrors and is termed the distributed Bragg pulse shaper (DBPS).

Several classes of pulse shapers or filters for optical data encoding have been previously considered, including Fourier-plane pulse shapers [5]–[8], holographic pulse shapers [4], [9], [10], acoustooptic tunable filters [11], coupled-waveguide filters [12], arrayed-waveguide gratings [13], [14], optical delay lines [15], and nonlinear interferometers [3], [16]. Pulse shapers for communications applications must 1) create data packets with terahertz bandwidth, 2) be reconfigurable at the data packet period, 3) be robustly packaged, and 4) interface well with integrated and fiber devices. The experiments presented here demonstrate the capability of the DBPS to satisfy 1). As an integrated single waveguide device, the DBPS is much more compact and robust than previously demonstrated pulse shapers and therefore satisfies 3) and 4) well. The ability of the DBPS to satisfy 2) is not addressed by the experiments presented here.

The conceptual basis of reflection grating pulse shapers was considered theoretically in [17] and passive integrated Bragg pulse shaping was demonstrated in [18]. Multiple grating filtering similar to the DBPS was considered in [19]. This paper describes an implementation of integrated distributed Bragg pulse shapers in an Al$_x$Ga$_{1-x}$As waveguide and demonstrates electrical modulation of ultrafast wavepackets.

II. DBPS DESIGN

As shown in Fig. 1, the DBPS encodes a serial ultrahast optical packet from a parallel set of electrical inputs. The device consists of a series of weak Bragg reflector segments acting on light propagating in a waveguide. An optical source pulse with center frequency matched to the nominal resonance of the Bragg reflectors is launched into the waveguide. As it propagates along the waveguide, the pulse is reflected (in a spatially distributed manner) from each Bragg grating segment, forming an output packet consisting of time-delayed reflections of the input. Contacts on each grating reflector allow electrical modulation of the refractive index in the vicinity of the reflector. A change in refractive index causes the Bragg resonance frequency of a modulated grating segment to shift. If the Bragg resonance of the segment is shifted sufficiently from the pulse center frequency, reflection ceases in that segment.

One may consider the distributed Bragg pulse shaper to be a series of partially reflecting mirrors. Each mirror may be turned on or off electrically. In device operation, the mirrors are set to a desired configuration of “ON” and “OFF” states, and then a source pulse is launched longitudinally through the mirrors. This source pulse is partially reflected by “ON” mirrors and is unaffected by “OFF” mirrors. An output packet is formed from reflections from “ON” mirrors, superimposed and delayed by the transit time to each “ON” mirror and back out of the device. Thus the temporal shape of the serial reflected field corresponds to the spatial pattern of mirror states. After the encoded wavepacket has left the device, the device is reconfigured for the next source pulse. The propagation time...
between mirrors determines the temporal separation of bits in the reflected signal. The total propagation time into the series of mirrors and back out determines the wavepacket length. In practice, multiple reflections and other second order scattering effects may alter this picture, but such effects can be accounted for in filter design [17].

Device geometry is an important issue in pulse shaper design. The reflection geometry offers two important advantages over transmission approaches. To understand the first advantage, it must be emphasized that wavepacket encoders can be considered as complex programmable filters. The spectral resolution of such filters depends on scattering geometry and device volume. The spectral resolution per unit device volume for reflection filters is orders of magnitude greater than for transmission approaches because the spectral sensitivity of reflective scattering is greater [20] and because the spectral sensitivity of reflection depends linearly on device length, while the sensitivity of transmission modulators is linear in device volume. The second advantage of reflection is that it allows spatially distributed modulation. A spatially local modulator, like a shutter, deformable mirror, or absorption switch, requires a very large change in effective index or absorption to obtain high contrast. A section of distributed Bragg reflector can achieve high contrast modulation using a change in effective index of less than one percent. Although similar results can be obtained by modulating distributed transmission modulators or Fabry–Perot filters, these devices extract a substantial cost in modulator volume or sensitivity.

Several factors ultimately limit the bandwidth attainable by the DBPS, including the magnitude and speed of attainable refractive index change, and the waveguide absorption. To switch a grating in the DBPS from the on to off state, one must shift the refractive index in the vicinity of a reflector such that the reflector is off-resonance with the input pulse. This occurs optimally when the spectral width of the grating is equal to the spectral width of the input pulse. To within factors on the order of two influenced by the exact pulse shape and grating spectrum, this is equivalent to saying that the grating reflection spectrum and the input pulse should have equal full-width at half maximum (FWHM), $\Delta \nu$. Then shifting the reflectivity of the grating by approximately $\Delta \nu$ will result in a sufficiently low overlap between the pulse spectrum and grating reflectivity spectrum to consider the reflector turned “off.” The frequency shift attainable by a given change in refractive index $\Delta n$ is $\Delta \nu = \Delta n c / \lambda n$, where $n$ is the refractive index of the material and $\lambda$ is the operating wavelength. Assuming a Gaussian transform-limited input pulse, this gives an optimal pulse with intensity FWHM $\Delta t \approx 0.5 \Delta \nu^{-2}$. The length of the required grating section is then calculated from the desired grating reflection bandwidth. As a rule of thumb, the length of the grating, $l$, should be approximately equal to the spatial length of a transform-limited source pulse in the material $l = c \Delta t / n_0$, as can be visualized in Fig. 1. Assuming spaces between grating sections also of length $l$, the DBPS will have a burst bit rate of $f = 1 / 4 \Delta t = \Delta n c / 2 \lambda n$. For example, in the case of our demonstration, an attainable index change of $\Delta n = 0.015$ at $\lambda = 760$ nm and $n = 3.4$ gives a burst bit rate of 0.4 THz, comparable to what is reported here.

In selected III–V semiconductor materials, refractive index changes as large as $\Delta n = 0.06$ with 15 ps response time [21] and other similar results have been reported [22]–[25]. Using such materials, one could expect burst bit rates of 2 THz. Note that because the attainable refractive index change does limit the source spectral width, it is possible to multiplex several distributed Bragg pulse shapers using wavelength division multiplexing techniques.

Ideally a DBPS would be operated quasicontinuously, such that the reconfiguration time of the pulse shaper were comparable to the packet length. The reconfiguration speed is limited by the lifetime of the effect causing the refractive index change. Again using the example above, a packet of equal length to a 15 ps reconfiguration time would consist of about 50 pulses, or a device 2.5 mm long. Assuming a continuous stream of 15 ps packets separated by 15 ps reconfiguration times, the total bit rate is 1 THz. Unfortunately, such a device may be impossible due to other practical factors such as waveguide absorption and dispersion and attainable electrical modulation speeds, but these equations give a convenient upper limit to what may be achieved. Several other practical issues are discussed later.

III. EXPERIMENTAL DEMONSTRATIONS

We have constructed several generations of DBPS prototypes in Al$_x$Ga$_{1-x}$As. This material system was chosen because of available fabrication technology, and for convenience of testing using a Ti: sapphire laser. Earlier pulse shapers were not contacted electrically, and thus could not be modulated. A 1 Tb/s pulse train generated by one such pulse shaper and detected by the method described below is shown.

Fig. 1. Schematic of the distributed Bragg pulse shaper.
High losses evident in this data packet are caused by several factors: strong reflection gratings, high waveguide losses, and radiation modes from third-order gratings into the substrate.

The switching experiments described here were done on the third generation device shown in Fig. 3. The device is fabricated as follows: the epitaxial layers are grown by metal organic chemical vapor deposition (MOCVD). The waveguide core is 0.53 μm symmetric parabolically-graded AlₓGa₁₋ₓAs, with Al composition ranging from 20% at the center to 30% at the outer edges, and low doping (n = 10¹⁷ cm⁻³). The large parabolic waveguide helps ease coupling difficulties. The lower cladding and buffer layer is 1.5 μm thick, doped n = 2 × 10²⁸ cm⁻³, and the upper cladding is 0.5 μm thick, doped p = 2 × 10¹⁸ cm⁻³. Both are AlₓGa₁₋ₓAs with 30% Al. A 0.1 μm GaAs cap layer prevents formation of native aluminum oxides on the surface, and provides good electrical contact. The cap layer is doped p = 1 × 10¹⁰ cm⁻³. The waveguide is a 3 μm wide ridge, etched to a depth 210 nm using a solution of 1 : 8 : 80 H₂SO₄ : H₂O₂ : H₂O.

The Bragg reflectors are sections of third-order grating etched into the surface of the waveguide. The gratings are created by a direct electron beam write in PMMA, and etched 280 nm into the epitaxial layers using reactive ion etching (RIE). The third order gratings are mandated by the resolution of the available equipment. The grating is etched continuously along the entire waveguide, alternating every 50 μm between 333 nm period to reflect λ = 758 nm, and 346 nm period to reflect λ = 780 nm. The pulse shaper is designed for use at the shorter wavelength, such that the active 333 nm gratings act as partial reflectors, while the 346 nm gratings have no effect. This continuous-grating design suppresses reflections observed in earlier devices arising from discontinuities between etched grating reflectors and unetched waveguide sections. Contacts consisting of 50 A Ti, 50 A Pt, and 1500 A Au are applied to each of the active grating sections, and the back of the device is metallized with 250 A Ge and 1350 A Au, alloyed at 390 C.

We demonstrate operation of the DBPS by modulating pulses from a mode-locked Ti:sapphire laser, using the experimental setup shown in Fig. 4. The laser generates 100 fs pulses. The 50 μm long grating sections are designed to match pulses with a coherence time of about 300 fs. The laser pulses are stretched to 300 fs coherence time by bandpass filtering in a single-sided Fourier-plane pulse shaper. The reduced-bandwidth pulse is split into a reference pulse and a source pulse. The source pulse is lens-coupled into the facet of the DBPS. The signal packet generated by the DBPS exits the same facet, and is focused by the lens through a beam splitter onto a CCD camera. The reference pulse is delayed by a mirror on a motorized stage and combined with the signal packet on the CCD camera. The signal packet is detected by digitizing the signal from the CCD camera using a commercial digitizing board. The CCD camera is oriented so that the fringes appear vertically on the monitor, and a single horizontal scan line captured from the monitor will show a sinusoidal variation in intensity due to the fringes. A narrow-band FFT-based filter is applied to the line data and integrated, and the result is the fringe visibility of the fringes, representing the electric field amplitude of the signal packet. Although this is a slow, repetitive-pulse measurement, a technique for fast single-shot cross-correlation has been proposed and demonstrated [26].

The DBPS can operate in two distinct modes: normally-on and normally-off. We demonstrate both of these possibilities experimentally. In the normally-on case, the input wavelength is tuned to the Bragg grating resonance, and shifting the index of a grating segment turns the reflection from that segment off. In the normally-off case, the input pulse is tuned off-resonance with the Bragg grating segments, such that a current-induced refractive index change turns the reflection on. For the normally-on case, the Ti:sapphire laser and Fourier-plane pulse shaper are set to produce pulses of wavelength at λ = 758.6 nm with a full width at half maximum (FWHM) of Δλ = 2.2 nm. The output packet generated by the device is measured with no current, and then measured again with dc currents of 5, 10, and 25 mA injected into the second grating of the device, to show various stages in the switching of one bit.
The modulated output waveforms from the DBPS with these currents are shown in Fig. 5. In this figure, the leftmost peak is a result of scattering from the front facet of the device, with a peak fringe visibility of 0.32. Precautions including antireflection coating and tilting the input facet have been taken to reduce this scattering, but some scattering remains due to roughness at the edge of the waveguide, and this appears strong in the measured data due to the high lens-coupling losses of the source pulse and shaped packet between free space and the AlGaAs waveguide. The four peaks after the initial reflection are data bits, and the four traces in the plot show various stages in switching the second bit off. Due to facet reflections and inefficient lens-coupling into a small AlGaAs waveguide, the reflectivity of the device could not be accurately measured. The designed reflectivity of the device is 1% per Bragg grating section. The variation in the shape of the first reflected pulse visible in Fig. 5 is due to the mode-locked laser briefly becoming unstable during data collection. If such a feature were caused by current spreading in the device, it would be symmetrical in the reflections on either side of the current injection. Although no such crosstalk is visible in the data, it is likely that practical DBPS devices would require some precautions be taken to limit current spreading.

For the normally-off case, the Ti:sapphire laser and Fourier-plane pulse shaper are set to produce pulses at $\lambda = 702.1$ nm with a FWHM of $\Delta \lambda = 2.2$ nm. The shaped packet is tested with current of 0 mA, and again with 17.5 mA dc current to turn on the reflection from the grating section. The data are presented in Fig. 6. Again, a front facet reflection is visible, with a peak visibility of 0.21.
The refractive index change caused by the current injection is measured by two distinct methods. In the first, the peak reflection wavelength of the Bragg grating was found as a function of input current. In the second method, the phase shift of light passing through the grating section was measured as a function of current, giving the change in the group refractive index.

To measure refractive index change by the first method, the reference motor was positioned to detect interference fringes caused by reflections from the grating with the wire-bonded contact (the second reflector). The laser and Fourier plane pulse shaper were tuned to find the wavelength for fringes of peak visibility. Then a range of dc currents was applied to the grating section and the wavelength giving peak fringe visibility was recorded. The results are presented in Fig. 7. A linear fit to the data, also pictured on the curve, gives the relation $\Delta n = 1.08 \times 10^{-3} I_g$, where $\Delta n$ is the change in refractive index, and $I_g$ is the dc current in the section of grating.

In the second method, measurements of path length were used to estimate the electrically induced change in the group refractive index. The reference motor was positioned such that interference fringes were visible on the monitor resulting from light that had traveled through the electrically contacted grating segment (the second reflector) and was reflected back by the segment beyond it (the third reflector). The phase shift $\Delta \phi$ of observed fringes was measured as a function of the input current. The direction of the motion of the fringes as a result of increasing dc current indicated an increased index, confirming the sign of the index change measured above. The index change is presented in Fig. 8, and is calculated from the path length change in two transits through the 50 $\mu$m section where current is injected. For this index change calculation, it is assumed that current spreading is negligible, such that the measured phase shift occurs only in the section of the waveguide that is covered by the 50 $\mu$m wide contact.

The positive sign of the measured refractive index change suggests that the index change observed is a result of thermal effects (of positive sign) in the material overshadowing free carrier plasma effects (of negative sign). This conclusion is
supported by the observations of similarly constructed tunable DBR lasers [27].

IV. DBPS MODEL

This section presents a model that confirms the observed response of the DBPS and predicts the response of an idealized device. The DBPS response is modeled by coupled-mode theory [28]. The distributed Bragg pulse shaper is modeled as a series of cascaded single-frequency gratings. The complex reflection coefficient $\Gamma(\omega)$ is found for a discrete series of wavelengths, and the inverse fast Fourier transform (FFT) gives the temporal impulse response of the device. This impulse response is convolved with the temporal shape of the input pulse to give the shaped packet.

To solve for the response of a complex grating using the coupled-mode equations, the complex structure is broken down into a series of simple grating sections, each with constant grating period and refractive index corrugation. The reflectivity and transmission of each grating section is determined using the one-dimensional coupled-mode equations presented in [28]. The coupled mode equations are solved analytically at a given optical frequency to give the right-propagating, $R_{n+1}(\omega)$, and left-propagating, $S_{n-1}(\omega)$, field amplitudes at the left side of a simple grating section as a function of the corresponding field amplitudes $R_n(\omega)$ and $S_n(\omega)$ at the right side of that section. To model the entire DBPS, we start with the boundary conditions at the end of the rightmost grating section $R_N(\omega) = 1$ and $S_N(\omega) = 0$, and find numerical values for $R_{N-1}(\omega)$ and $S_{N-1}(\omega)$. The field amplitudes are continuous at the boundary to each successive grating section, allowing the solution at the left side of a grating section to be used as the boundary condition at the right side of the next section. In this way, the entire cascade of simple grating sections is solved for the input and output fields at the entrance to the DBPS, $R_0(\omega)$ and $S_0(\omega)$. The reflection coefficient for the DBPS $\Gamma(\omega) = S_0(\omega)/R_0(\omega)$ is then solved for a discrete series of optical frequencies. This type of model is also used to model fiber Bragg gratings [29]. At this point $\Gamma(\omega)$ is either inverse Fourier transformed to find the impulse response, or it is multiplied by a known input pulse spectrum and inverse Fourier transformed to find the output of the device for that particular input pulse. The advantage of this model over simply modeling the device as a series of partial reflections is that this model inherently includes the effect of multiple reflections. Multiple reflections from weak gratings are too weak to show up in the measured or simulated data.

Fig. 9 shows a model predicting the experimental behavior for the DBPS presented in this paper. This model uses the measured grating period and length, and the measured spectrum of the input pulse. The amplitude of the refractive index modulation in the grating is calculated using the effective index method. The effective index of the mode and its dispersion, assumed linear over the frequency range of interest, are fit to the observed data. Because this model uses numerical solutions at a series of discrete frequencies, a linear refractive index dispersion for the AlGaAs waveguide was easily included. This refractive index dispersion gives a group index for the mode of $n_g = n + \lambda_0 \delta n / d\lambda = 4.1$, which can be confirmed by measuring the distance between reflections from the 50 $\mu$m grating sections. The loss coefficient due to waveguide absorption and substrate radiation loss caused by the third-order grating is also fit to the observed data. To match the actual tested device as well as possible, the DBPS model includes a front facet reflection, calculated from the measured spectrum of the input pulse. Finally, the calculated output field is correlated with the measured spectrum of the reference pulse, to simulate the interferometric cross-correlation detection. This simulation is repeated for several values of injected current (for which the refractive index change is measured above), showing switching behavior of the second bit. Comparison between Figs. 5 and 9 reveals excellent agreement between the model and observed data. We were also able to obtain equally good agreement in simulating the normally-off case.

The calculated frequency response of the DBPS for the case of 25 mA current is shown in Fig. 10, with the measured input pulse spectrum superimposed. Several features are visible in the reflection spectrum of the pulse shaper. Reflections from the gratings of 333 and 346 nm period show fine structure due to the superposition reflections of several grating sections at varying time delays. The reflection from the 333 nm grating
that has been shifted to longer wavelength by the current injection is also visible in the spectrum, showing that the index change has moved the grating off-resonance with the input pulse, and thus switched it off.

V. CONCLUSION

We have introduced the DBPS, demonstrated a successful proof of principle of device operation, and provided a model corroborating the observed response. For the device to become practical, several higher order aspects of DBPS design must be considered. These include operating wavelength, materials structure, multiple reflections, and wavepacket equalization. All of these issues can be addressed by careful device design. Practical devices must operate in the 1.3 and 1.5 mm communications bands, in materials with appropriate modulation ability. As mentioned above, several III–V semiconductor materials look promising for a material that can provide the large ultrafast refractive index changes that will be necessary for a high-bandwidth DBPS at 1.5 μm. This longer-wavelength regime also has the advantages of larger first-order gratings and large single-mode waveguides to ease coupling and fabrication constraints.

It is known that the correspondence between spatial grating shape and temporal pulse shape in reflective pulse shapers breaks down when the total device diffraction efficiency exceeds 50% [17]. In general, higher diffraction efficiencies lead to depletion of the source pulse and multiple reflections which distort the output packet. Simple modeling based on approximating the DBPS as a set of discrete mirrors shows that when the total DBPS diffraction efficiency is on the order of 25%, multiple reflections are reduced to reasonable levels (order of 10^(-4) or 10^(-5), and the last pulse in the packet is half the intensity of the first. For example, a pulse shaper with 30 grating sections would have reflectivity 1% per grating, 25% diffraction efficiency, and multiple reflections 1.3 x 10^(-4) weaker than signal pulses. The diffraction efficiency is not 30%, due to gradual depletion of the source pulse, which gives a signal packet with the last pulse half the intensity of the first. Insensitivity to multiple reflections in the DBPS arises from the fact that multiply reflected pulses must undergo three (weak) reflections from grating sections to exit through the output facet, and that multiply-reflected pulses from different paths will have randomly distributed phases, reducing the effect of combined multiple reflections. An improved design would involve apodization of grating reflectivities, such that all pulses in the packet have equal amplitude. This can be accomplished by either shadow masking of the RIE to etch deeper gratings toward the back of the device, or by varying the duty cycle of the second- or third-order gratings to reduce the reflectivity near the front of the device. Simulations of apodized devices also produce good results for total efficiencies of 25%. Higher efficiency devices could be realized using more complex schemes involving nonlocal programming of the parallel drive signals.

The large front-facet reflections observed in the experimental data can be reduced or eliminated in alternate designs that ease coupling constraints. Practical devices will rely on efficient coupling between the source, DBPS, and fiber, possibly including tapered waveguides, and integration including couplers, amplifiers, LED’s, and mode-locked laser diode sources. However, front- or rear-facet reflections may also be used to advantage to provide reference pulses when the DBPS is used in the coherence domain multiplexed system [1].

REFERENCES

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