



(19) **United States**

(12) **Patent Application Publication**
Scalora

(10) **Pub. No.: US 2002/0135853 A1**

(43) **Pub. Date: Sep. 26, 2002**

(54) **PHOTONIC BAND GAP DEVICE AND METHOD USING A PERIODICITY DEFECT REGION DOPED WITH A GAIN MEDIUM TO INCREASE PHOTONIC SIGNAL DELAY**

(57) **ABSTRACT**

(76) Inventor: **Michael Scalora, Huntsville, AL (US)**

Correspondence Address:
STERNE, KESSLER, GOLDSTEIN & FOX PLLC
1100 NEW YORK AVENUE, N.W., SUITE 600
WASHINGTON, DC 20005-3934 (US)

(21) Appl. No.: **10/153,455**

(22) Filed: **May 24, 2002**

Related U.S. Application Data

(63) Continuation of application No. 09/572,290, filed on May 17, 2000, now Pat. No. 6,396,617.

(60) Provisional application No. 60/134,536, filed on May 17, 1999.

Publication Classification

(51) **Int. Cl.⁷ G02F 1/03; G02F 1/07**

(52) **U.S. Cl. 359/248; 359/254; 359/245**

A photonic band gap structure device and method for delaying photonic signals of a predetermined frequency and a predetermined bandwidth by a predetermined delay is provided. A Fabry-Perot delay line device has several regions of periodically alternating refractive material layers which exhibit a series of photonic band gaps and a periodicity defect region, interposed between the regions of periodically alternating refractive material layers. The Fabry-Perot delay line device imparts a predetermined delay to photonic signals that pass therethrough. The introduction of the periodicity defect region into this photonic band gap structure creates a sharp transmission resonance within the corresponding photonic band gap of the structure and causes at least an order of magnitude improvement in photonic signal delay for a band-edge delay line device of similar size. Variable photonic delays to multiple photonic signals are also generated by this Fabry-Perot delay line device. In addition, a photonic signal delay device based on an optical fiber grating structure is provided. A defect layer doped with a gain medium increases the density of modes thereby increasing the density of photons at a particular frequency. The introduction of gain automatically causes an increase in the photon density, and therefore, a narrowing of the density of modes. This allows tuning of the group velocity, just as if periods were being added. This also enables larger delays.

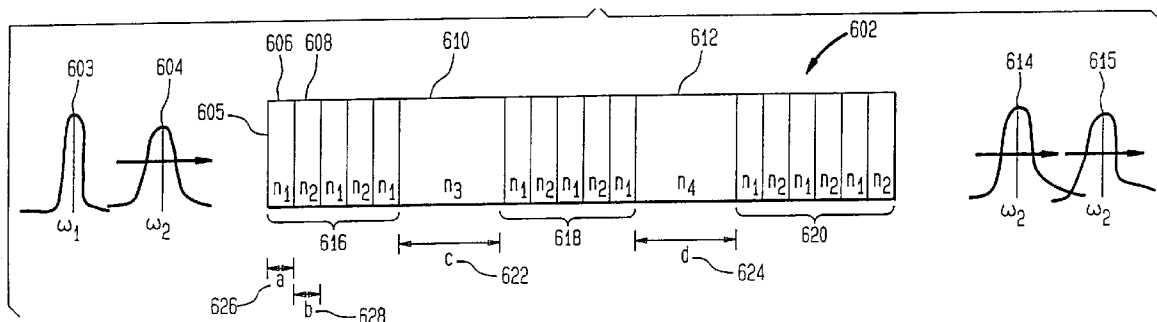
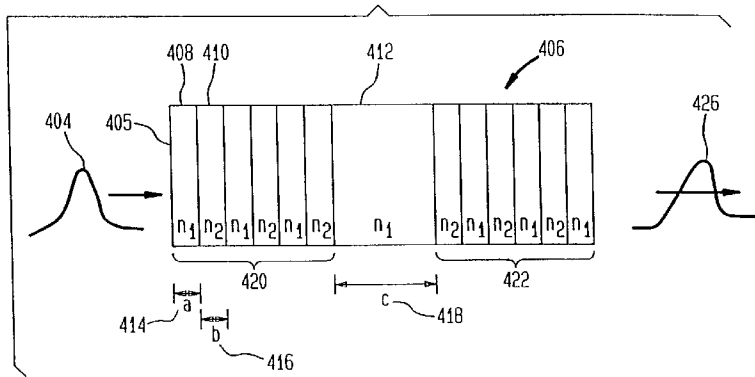


FIG. 1A
(PRIOR ART)

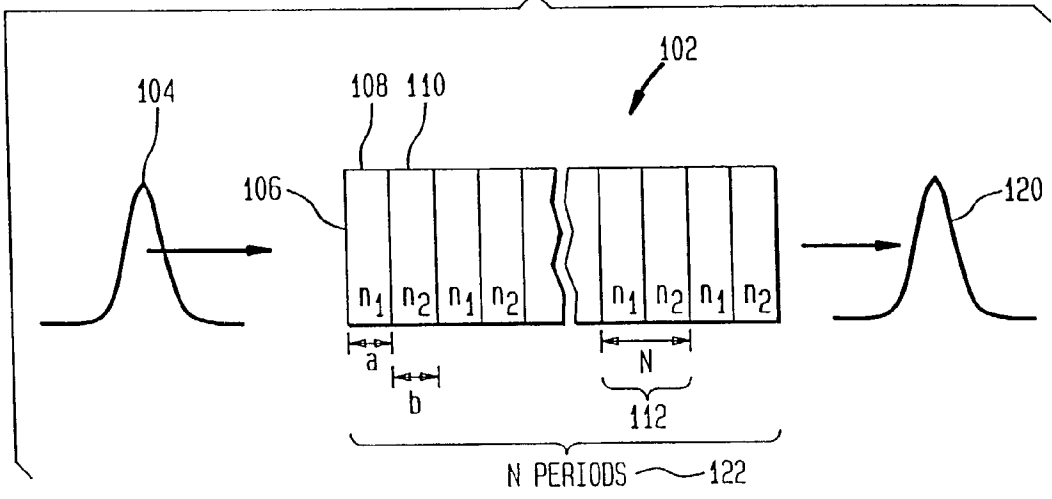


FIG. 1B
(PRIOR ART)

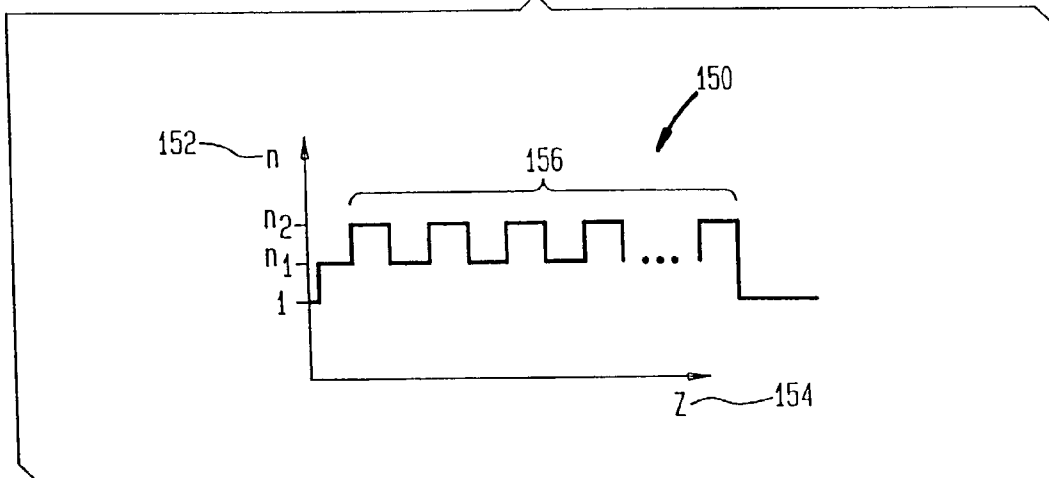


FIG. 2A
(PRIOR ART)

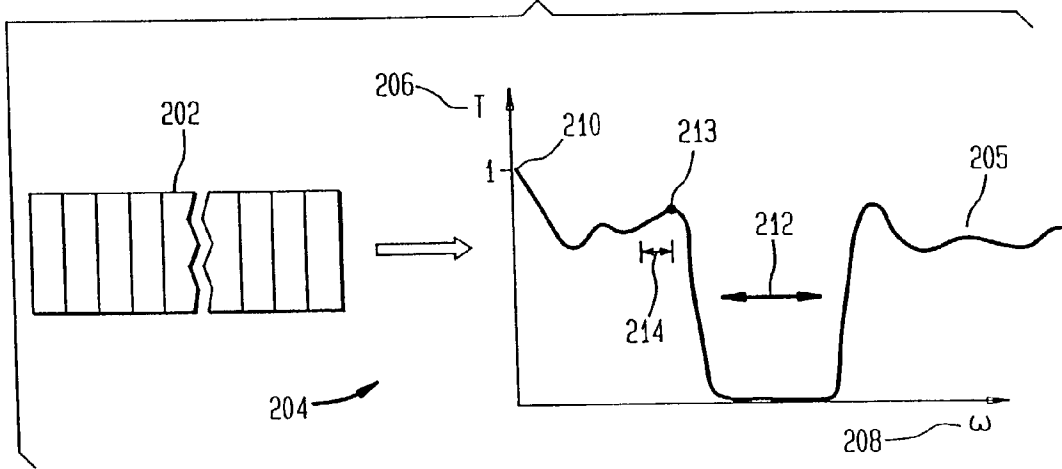


FIG. 2B
(PRIOR ART)

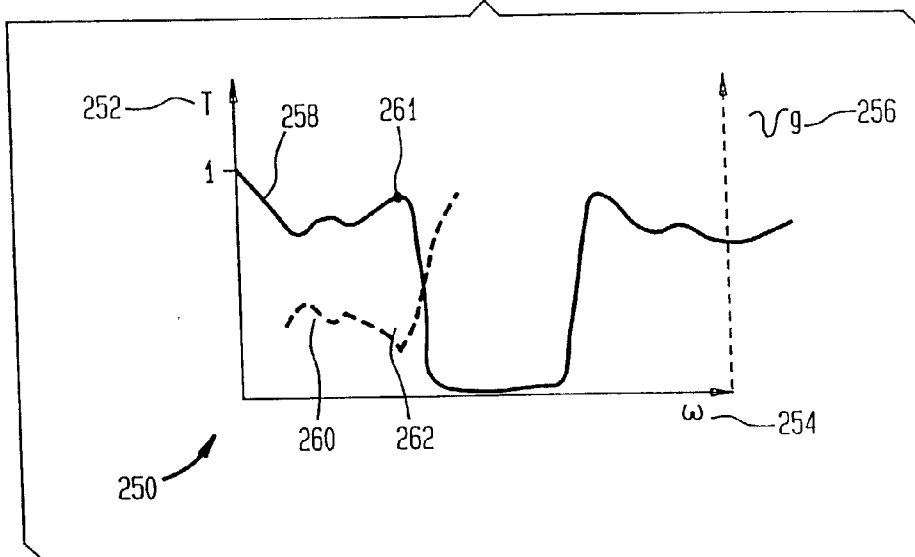


FIG. 3A
(PRIOR ART)

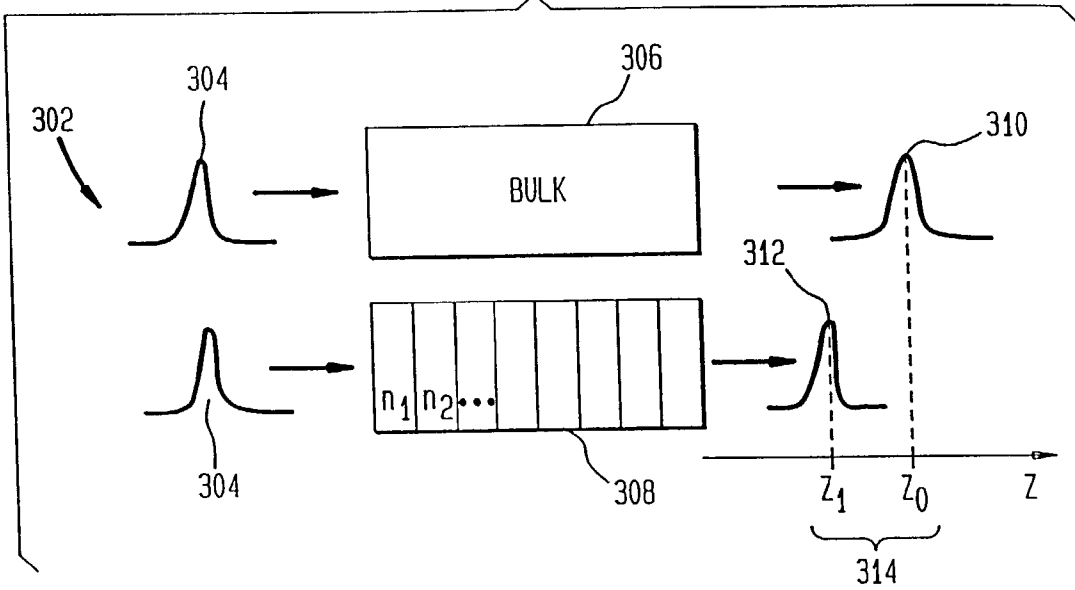


FIG. 3B
(PRIOR ART)

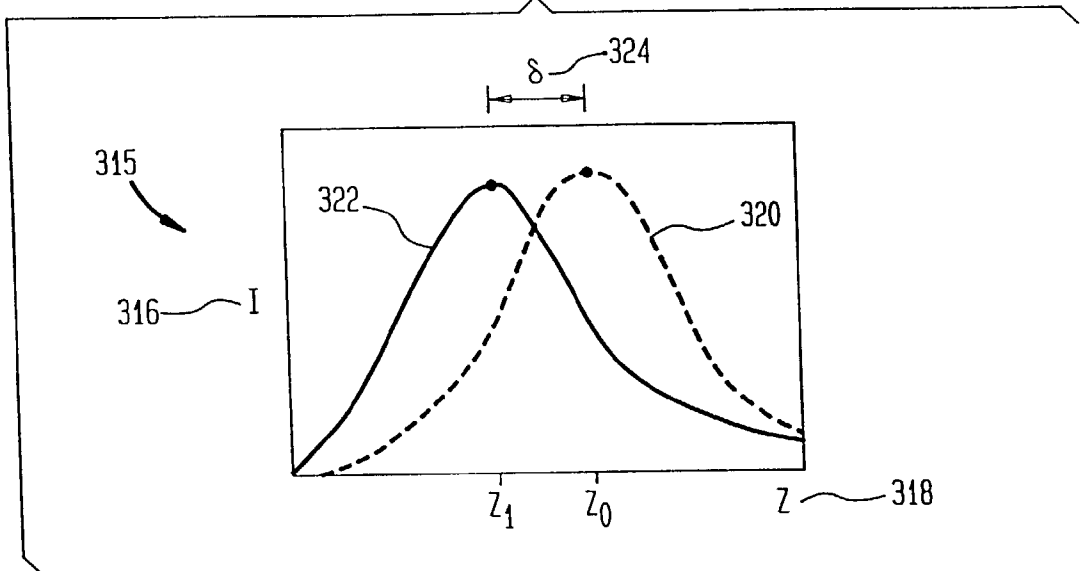
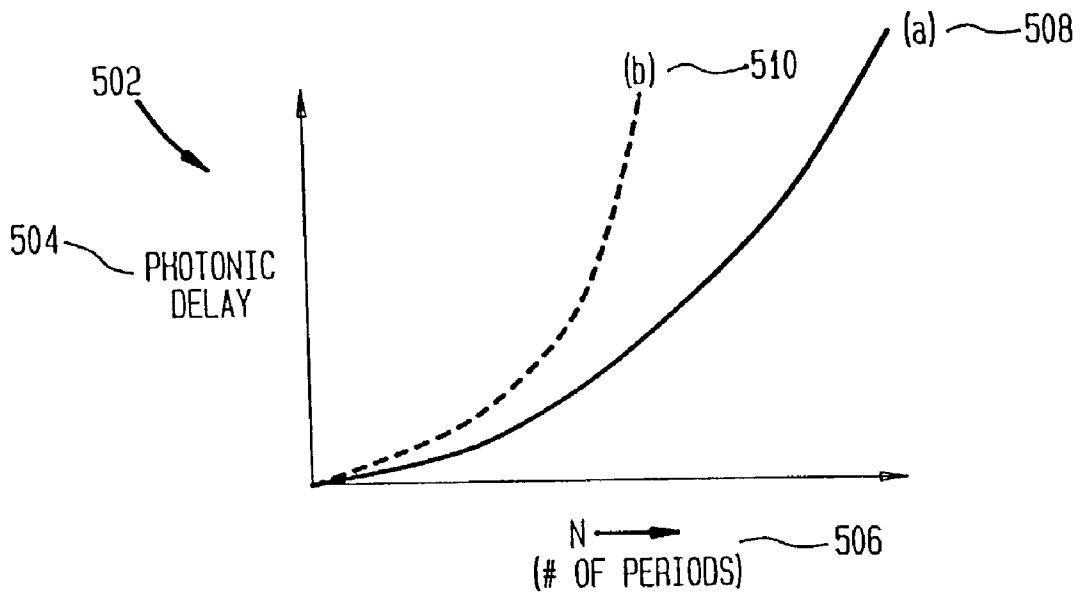


FIG. 5



(a) = BAND EDGE DELAY LINE DEVICE
(b) = FABRY-PEROT DELAY LINE DEVICE

FIG. 6A

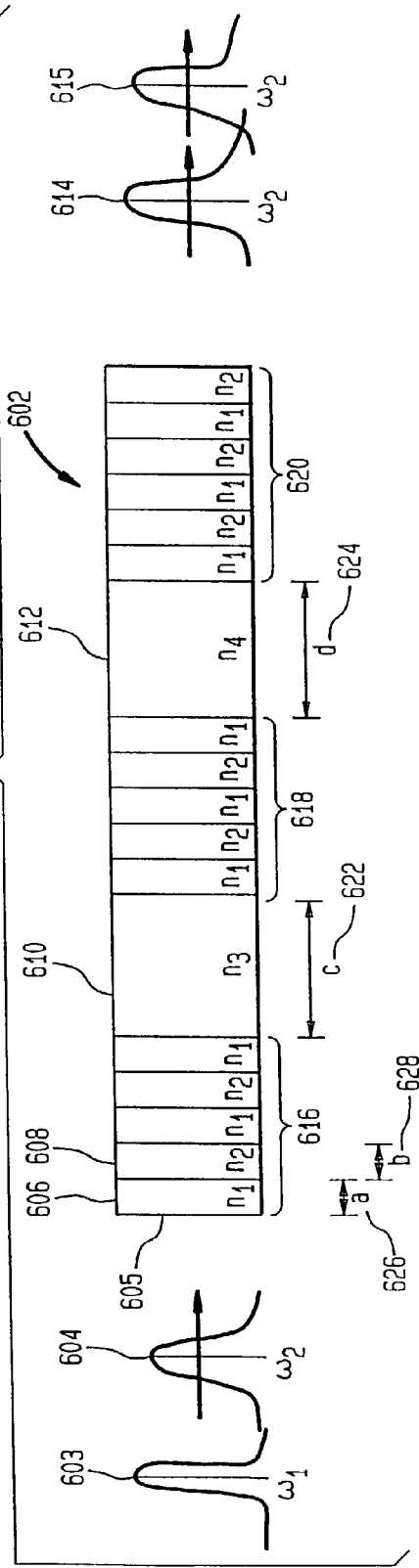


FIG. 6B

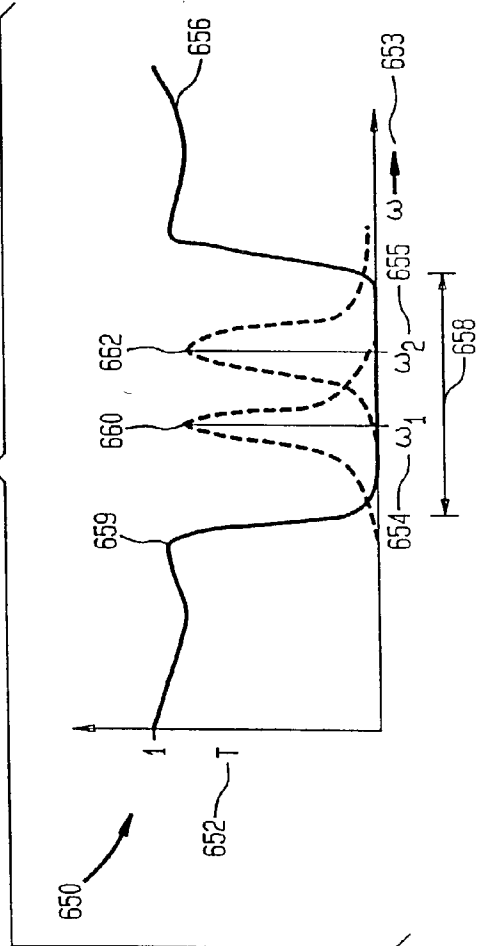


FIG. 7

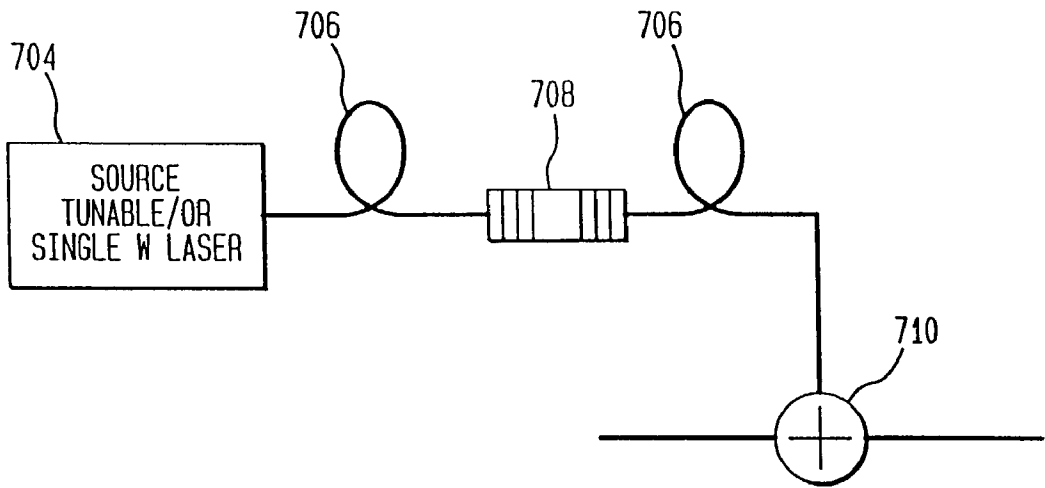
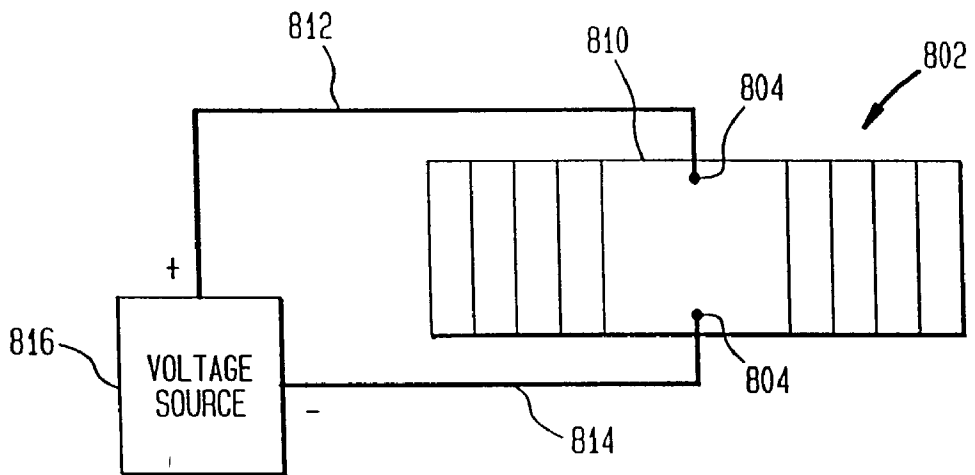


FIG. 8



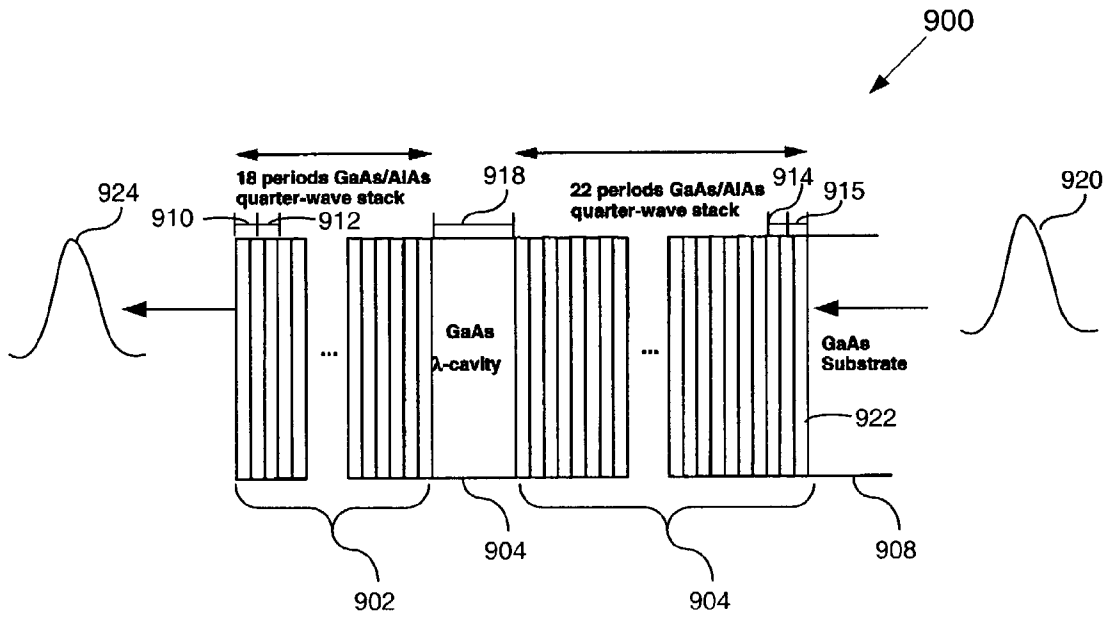


FIG. 9

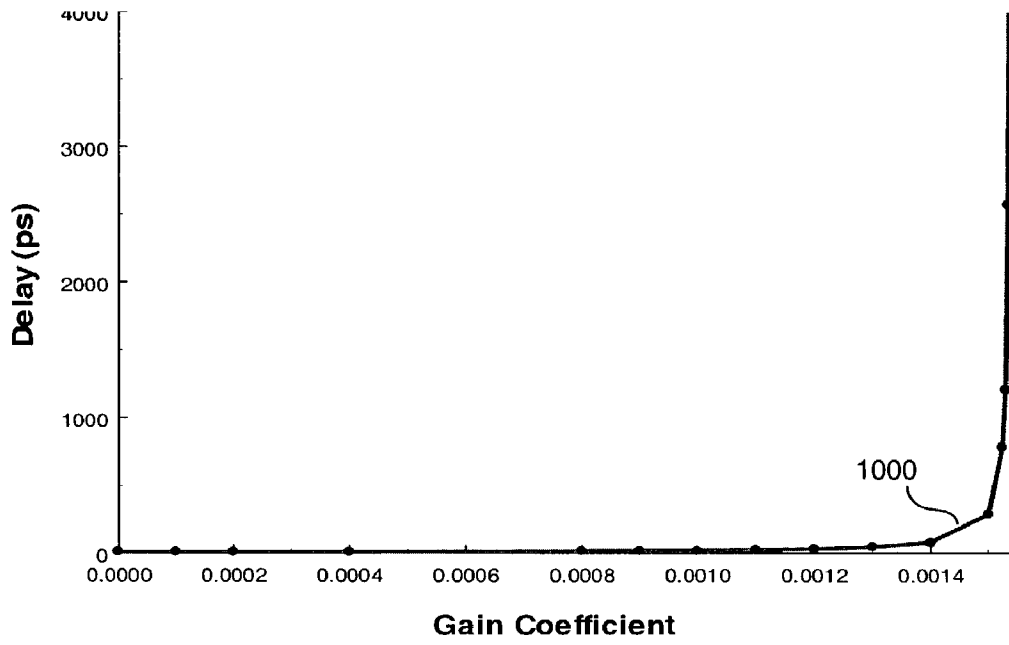


FIG. 10

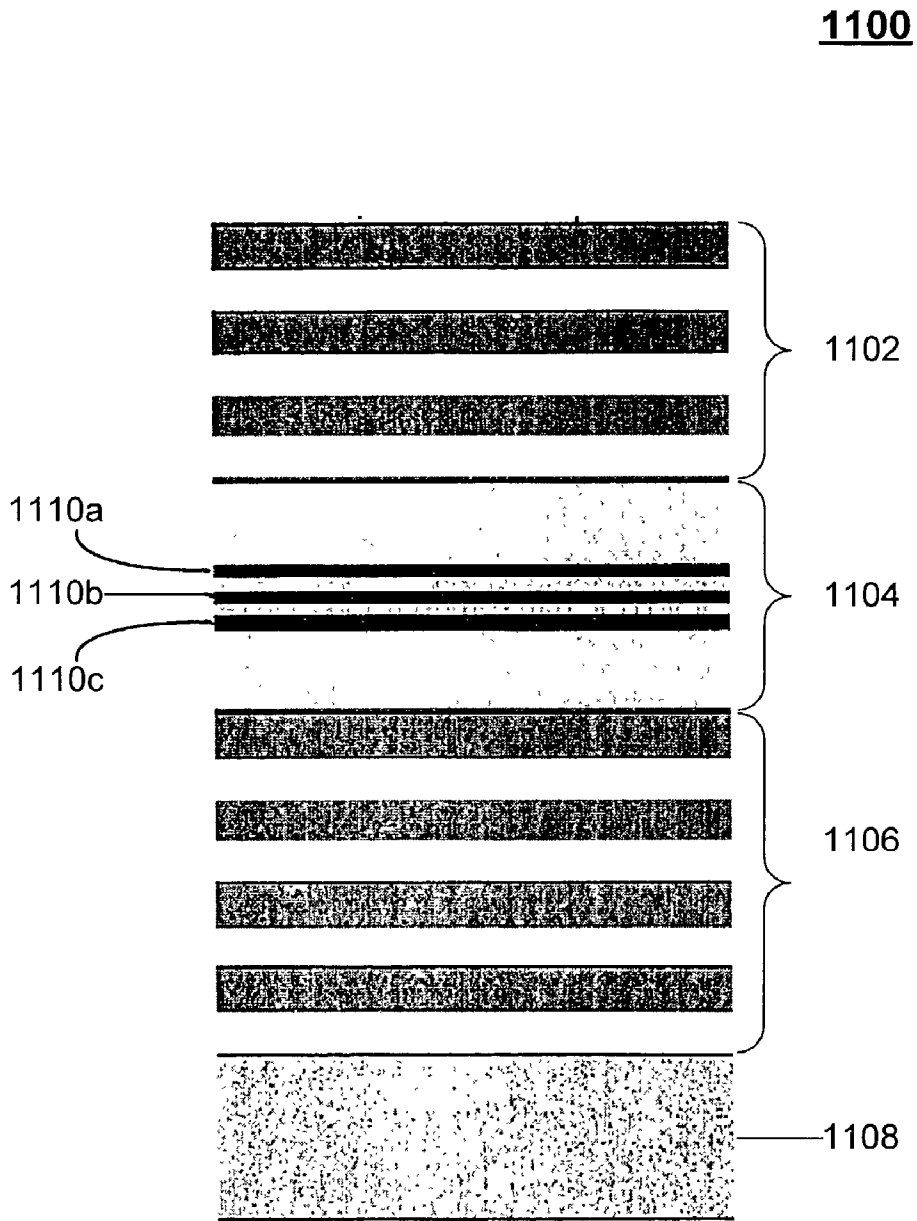


FIG. 11

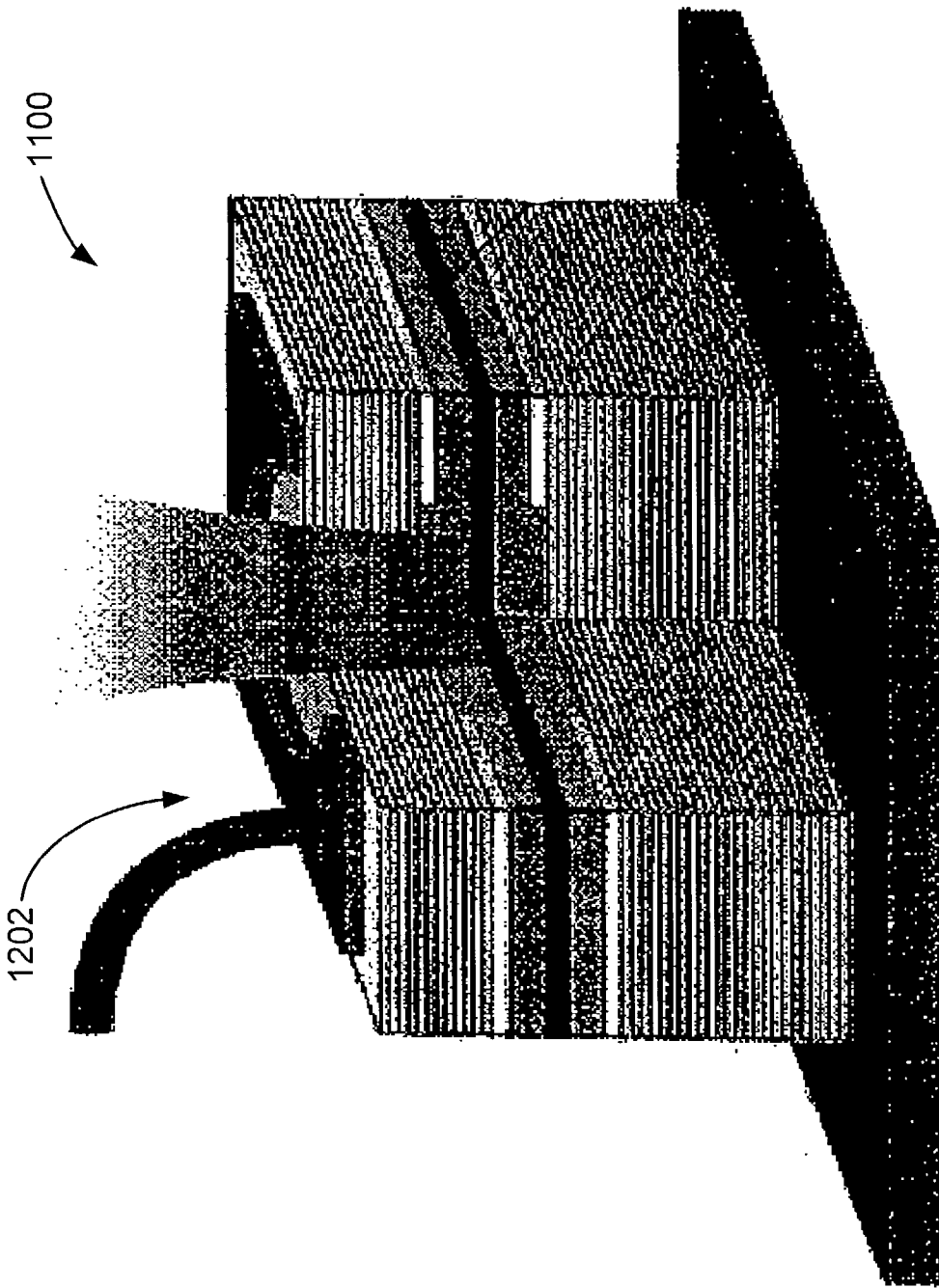


FIG. 12

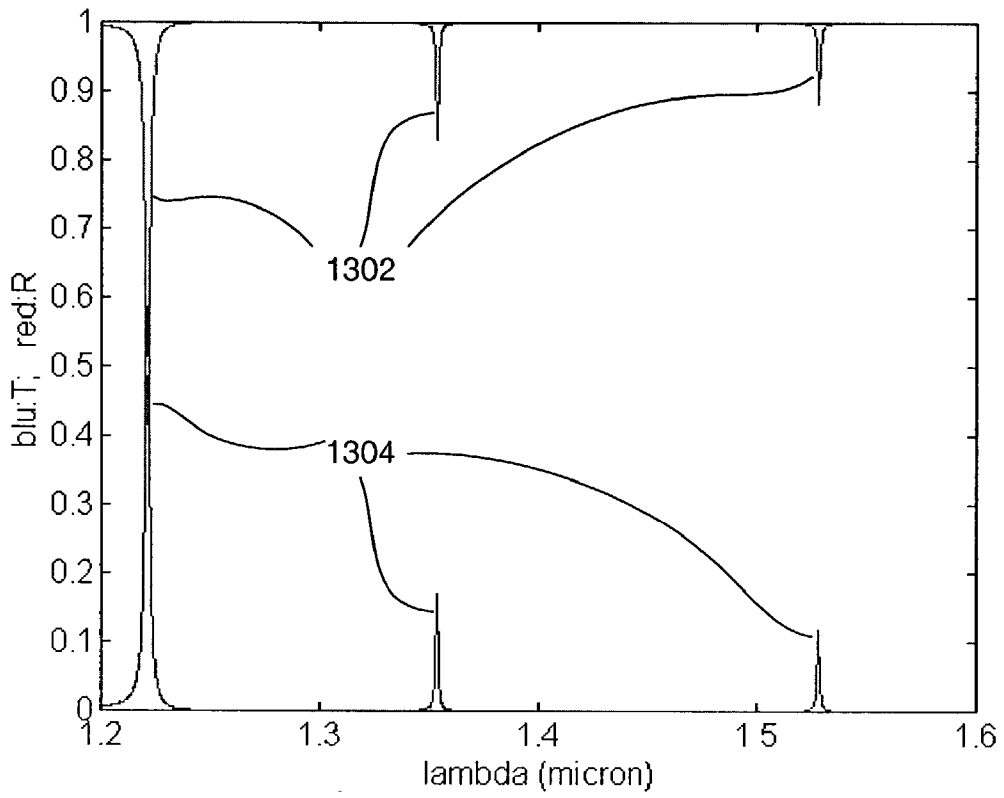


FIG. 13

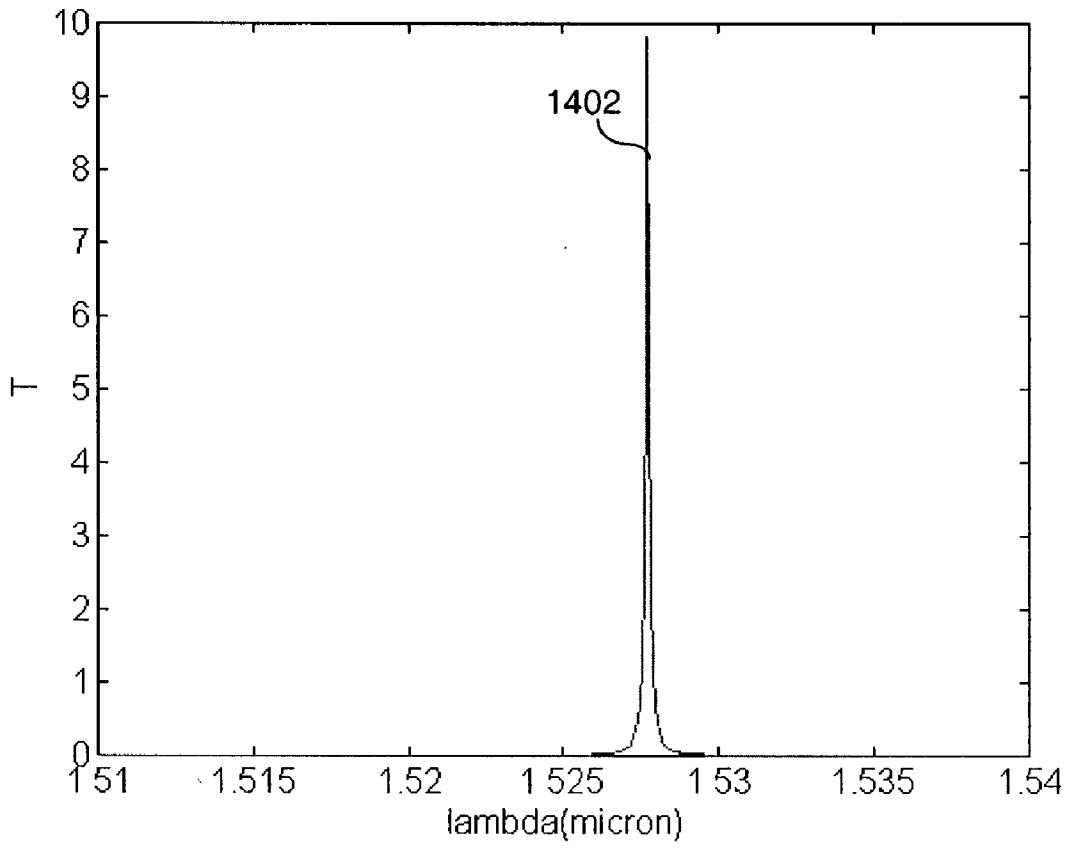


FIG. 14

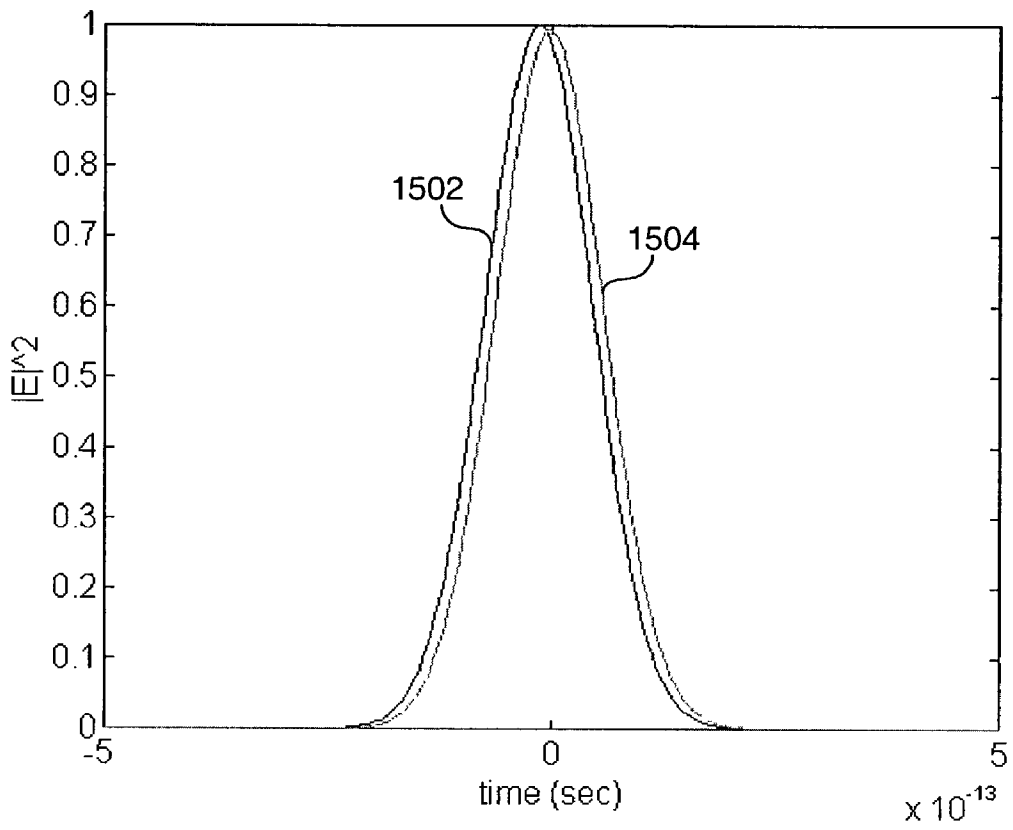


FIG. 15

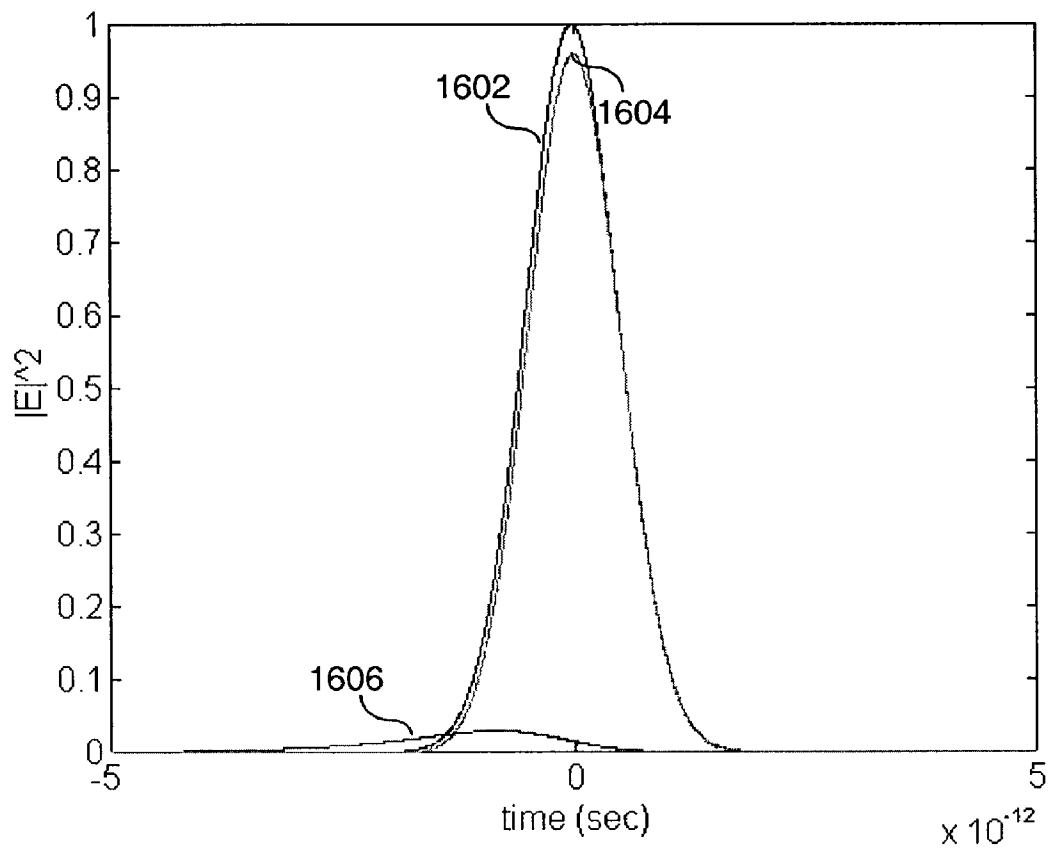


FIG. 16

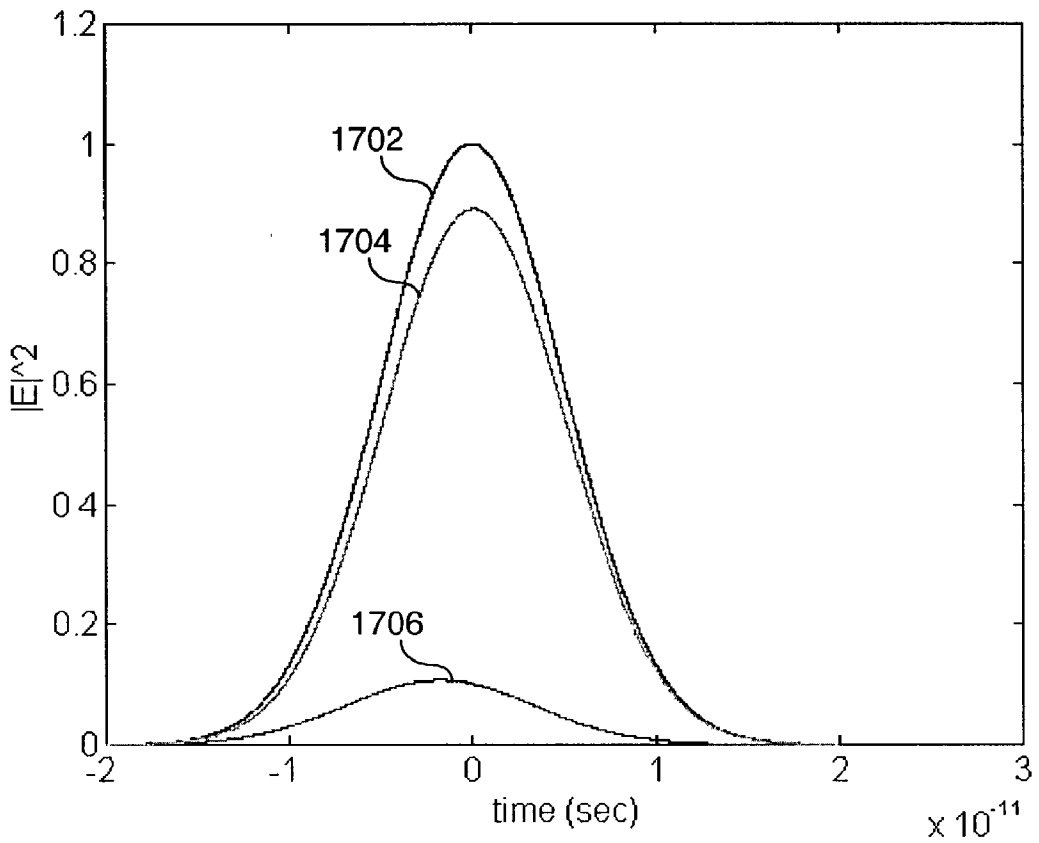


FIG. 17

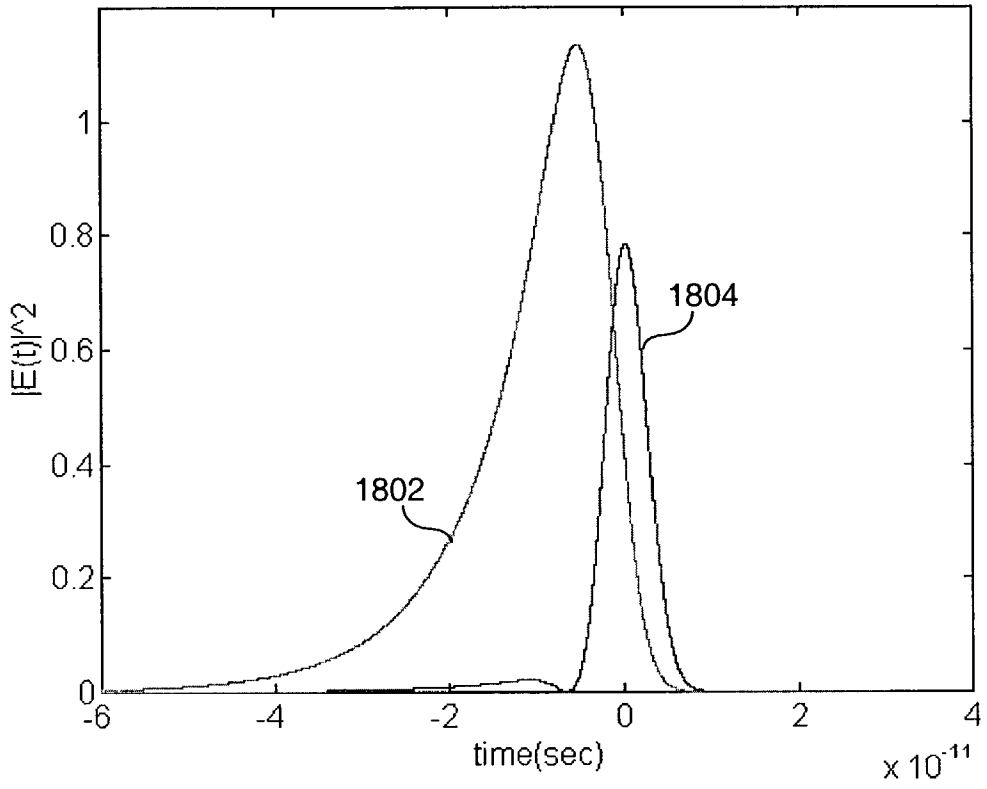


FIG. 18

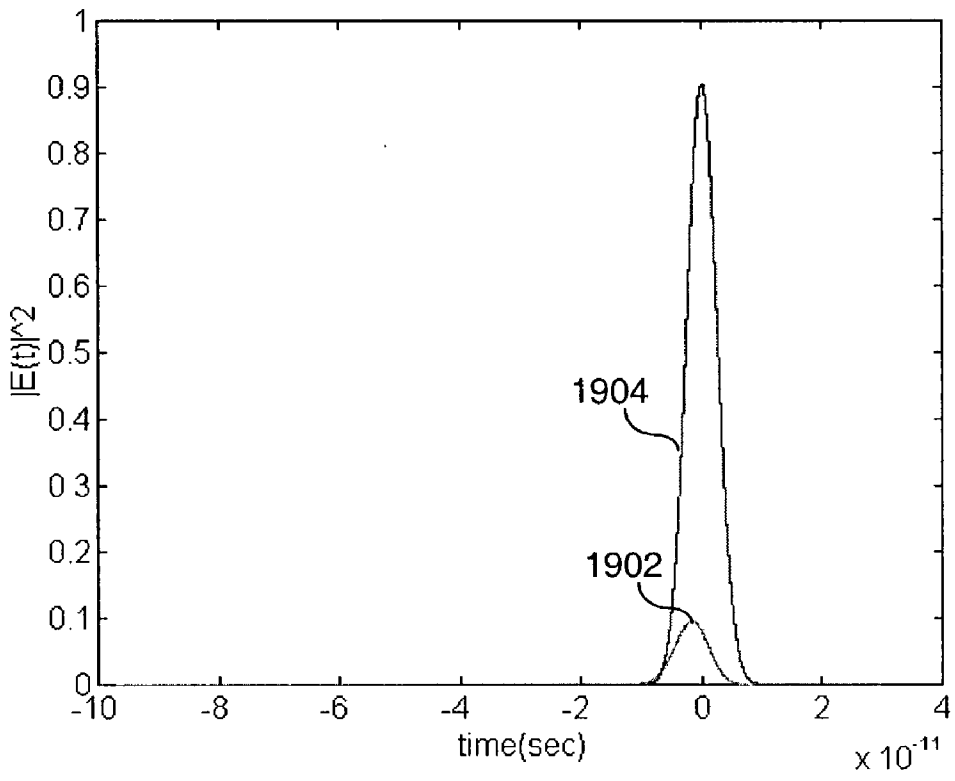


FIG. 19

**PHOTONIC BAND GAP DEVICE AND METHOD
USING A PERIODICITY DEFECT REGION DOPED
WITH A GAIN MEDIUM TO INCREASE
PHOTONIC SIGNAL DELAY**

**CROSS-REFERENCE TO RELATED
APPLICATIONS**

[0001] This patent application claims priority to and is entitled to the benefit of U.S. Provisional Patent Appl. No. 60/134,536, filed May 17, 1999, and U.S. Nonprovisional patent application Ser. No. 09/572,290, filed May 17, 2000, now allowed, entitled "Photonic Band Gap Device and Method Using a Periodicity Defect Region Doped with a Gain Medium to Increase Photonic Signal Delay." These applications are incorporated herein by reference in their entireties.

**FEDERALLY SPONSORED RESEARCH AND
DEVELOPMENT**

[0002] This invention was made with Government support under Contract DAAH01-96-R234 awarded by the U.S. Army Missile Command. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

[0003] 1. Field of the Invention

[0004] The present invention relates to optical communications and optical signal control. In particular, the present invention relates to an optical device and method for delaying photonic signals.

[0005] 2. Related Art

[0006] The fields of communications and data processing are currently transitioning from using electrical signals to using optical signals. As a result, there is an increased need for optical devices that perform various tasks in the control of these optical signals. Such devices include delay blocks for synchronizing optical pulses for communications. The synchronization of optical pulses requires the use of controllable delay devices which do not significantly distort the optical beam as it passes through the device. In particular, robust, compact, lightweight delay devices for use with a variety of predetermined optical frequencies must be developed to be easily integrated into existing optical systems.

[0007] One method of creating a low distortion, controllable photonic delay is through the use of "uniform" photonic band gap (PBG) structures, also called band-edge delay line devices. Uniform PBG structures typically comprise a stack of alternating layers of refractive materials of similar thicknesses, such as gallium arsenide and aluminum arsenide, which exhibit photonic band gaps in their transmission spectra. These alternating layers have different indices of refraction and can be deposited by well known deposition techniques onto a substrate.

[0008] By sending a photonic signal of a given frequency (ω) through this type of delay device, the discontinuity of the indices of refraction imparts a delay to the photonic signal. These devices slow down the photonic signal as a result of scattering inside the uniform PBG structure. Since the photonic delay is proportional to the square of the number of periods contained in the uniform PBG structure,

a device can be constructed that imparts a predetermined delay to a photonic signal. The physical processes involved in the photonic signal delay imparted by a uniform PBG structure are described in detail in Scalora, et al., "Ultrashort pulse propagation at the photonic band edge: large tunable group delay with minimal distortion and loss," Phys. Rev. E Rapid Comm. 54(2), R1078-R1081 (August 1996), which is incorporated by reference herein.

BRIEF SUMMARY OF THE INVENTION

[0009] The present invention generally relates to a device and method of creating an optical signal delay using a compact and readily manufacturable structure. In particular, the present invention interposes a periodicity defect region into a uniform photonic band gap (PBG) structure in order to generate a transmission resonance spike of very narrow bandwidth at or near the center of the photonic band gap of the structure. The introduction of this periodicity defect causes at least an order of magnitude greater photonic signal delay duration than for a uniform PBG device of similar size.

[0010] According to one embodiment of the present invention, a Fabry-Perot delay line device is provided for delaying photonic signals of a predetermined frequency and a predetermined bandwidth by a predetermined delay. The Fabry-Perot delay line device includes a first region of periodically alternating layers of refractive materials which exhibit a photonic band gap structure, a second region of periodically alternating layers of refractive materials which also exhibit a photonic band gap structure, and a periodicity defect region interposed between the first and second alternating layer regions. The first region of periodically alternating layers of refractive materials comprises one or more first refractive material layers having a first thickness and a first index of refraction, and one or more second refractive material layers having a second thickness and a second index of refraction. The second region of periodically alternating layers of refractive materials comprises one or more third refractive material layers and one or more fourth refractive material layers. The third refractive material layer has a thickness and an index of refraction similar to or identical to the first refractive material layer of the first alternating layer region. The fourth refractive material layer has a thickness and an index of refraction similar to or identical to the second refractive material layer of the first alternating layer region. The interposed periodicity defect region has a different thickness than either the first or second thickness of the alternating layers of refractive materials in the first and second alternating layer regions. Additionally, the periodicity defect region can have a third index of refraction and a photonic transmission resonance, which are predetermined along with thickness to impart predetermined delay to the photonic signals that pass therethrough.

[0011] According to one feature of the present invention, the transmission resonance due to the interposition of this periodicity defect region is located in the center of the photonic band gap. Further, the transmission resonance corresponds to the predetermined frequency of the photonic signal traveling through the Fabry-Perot delay line device.

[0012] According to a preferred embodiment of the present invention, the Fabry-Perot delay line device is constructed on a semiconductor substrate using semicon-

ductor materials, such as aluminum arsenide (AlAs) and gallium arsenide (GaAs), as the first and second refractive material layers, respectively. Additionally, the periodicity defect region is also a semiconductor material.

[0013] According to a second embodiment of the present invention, the Fabry-Perot delay line device includes two or more periodicity defect regions interposed between the periodically alternating layer regions. This embodiment provides for delaying photonic signals of differing predetermined frequencies and predetermined bandwidths by a predetermined range of photonic signal delays.

[0014] According to one feature of the second embodiment of the present invention, the first and second photonic transmission resonances are located at different frequency positions in the corresponding photonic band gap of the Fabry-Perot delay line device. Further, the first transmission resonance corresponds to a first predetermined photonic signal frequency, and the second transmission resonance corresponds to a second predetermined photonic signal frequency. Thus, the device may impart different predetermined delays to the first and second predetermined photonic signals traveling therethrough.

[0015] According to a third embodiment of the present invention, a tunable laser source generates photonic signals traveling through a Fabry-Perot delay line device. The delay imparted by the device varies as a function of the frequency of the photonic signals that pass therethrough.

[0016] According to another embodiment of the present invention, Fabry-Perot delay line device also includes electrical contacts located on the periodicity defect regions. A power supply source is coupled to the contact points to impart a variable voltage across the device which varies the indices of refraction of the periodicity defect regions, thereby varying the delay imparted to photonic signals passing therethrough.

[0017] Further, according to another embodiment of the present invention, both the band-edge or the Fabry-Perot delay line device can also be constructed using an optical fiber grating. According to this embodiment of the present invention, a fiber grating delay device comprises regions of alternating first and second sections, each section having a different index of refraction, which are periodically spaced along the fiber or waveguide. In addition, a periodicity defect region having a thickness from either the first or second section can be interposed between the regions of alternating sections. Further, piezo-electric or other suitable means can be coupled to the periodicity defect region to alter the optical path length of the periodicity defect region, thereby varying the photonic delay imparted to a photonic signal passing through the fiber grating delay device.

[0018] According to another embodiment of the present invention, a defect layer is doped with a gain medium.

[0019] Further features and advantages of the present invention, as well as the structure and operation of various embodiments of the present invention, are described in detail below with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

[0020] The present invention is described with reference to the accompanying drawings. In the drawings, like reference numbers indicate identical or functionally similar elements. Additionally, the left-most digit(s) of a reference number identifies the drawing in which the reference number first appears.

[0021] FIG. 1A is a schematic representation of a photonic signal delay device with a uniform PBG structure. This device is also referred to as a band-edge delay line device.

[0022] FIG. 1B is a diagram of the characteristic index of refraction profile of the uniform PBG structure shown in FIG. 1A.

[0023] FIG. 2A is a characteristic transmission profile for the band-edge delay line device shown in FIG. 1A.

[0024] FIG. 2B is a transmission profile for the band-edge delay line device that also includes a group velocity curve for a photonic signal traveling through the structure.

[0025] FIG. 3A is a schematic representation showing a photonic delay imparted by the band-edge delay line device of FIG. 1A.

[0026] FIG. 3B is a plot of the photonic delay imparted by the same band-edge delay line device.

[0027] FIG. 4A is a schematic representation of a PBG structure photonic signal delay device according to one embodiment of the present invention. This device is herein referred to as a Fabry-Perot delay line device.

[0028] FIG. 4B is a characteristic transmission profile for the Fabry-Perot delay line device of FIG. 4A.

[0029] FIG. 5 is a graph representing photonic signal delay as a function of the number of periods that compares a band-edge delay line device to a Fabry-Perot delay line device according to the present invention.

[0030] FIG. 6A is a schematic representation of a Fabry-Perot delay line device containing two periodicity defect regions according to a second embodiment of the present invention.

[0031] FIG. 6B is the corresponding transmission profile for the photonic signal delay device containing two periodicity defect regions shown in FIG. 6A.

[0032] FIG. 7 is a schematic representation of a tunable laser source, according to a third embodiment of the present invention.

[0033] FIG. 8 is a schematic representation of the Fabry-Perot delay line device of FIG. 7 having a voltage applied to the device.

[0034] FIG. 9 is a schematic representation of a GaAs/AlAs PBG structure.

[0035] FIG. 10 depicts delay versus gain coefficient for the structure depicted in FIG. 9.

[0036] FIGS. 11 and 12 provide two views of a vertical cavity surface emitting laser (VCSEL), according to the present invention.

[0037] FIGS. 13-19 are plots illustrating VCSEL performance.

DETAILED DESCRIPTION OF THE
INVENTION

Table of Contents

- [0038] 1. Overview and Discussion of the Invention
- [0039] 2. Terminology
- [0040] 3. Example Environment
- [0041] 4. Band-edge Delay Line Devices
- [0042] 5. Fabry-Perot Delay Line Devices
- [0043] a. Interposed Periodicity Defect in a Semiconductor Structure
- [0044] b. Multiple Periodicity Defects
- [0045] c. Variable Photonic Signal Delay
- [0046] d. Fiber Grating Photonic Delay Devices
- [0047] e. Defect Layer Doped with a Gain Medium
- [0048] 6. Conclusion
- [0049] Overview and Discussion of the Invention
- [0050] The present invention improves the current state of the art of photonic delay devices by interposing a periodicity defect into a uniform PBG structure in order to create a Fabry-Perot delay line device having a longer duration optical signal delay and which is compact and readily manufacturable. A Fabry-Perot delay line device, according to the present invention, can have an order of magnitude longer duration photonic signal delay compared to a uniform PBG structure of similar size.
- [0051] According to the present invention, the introduction of a periodicity defect into a uniform PBG structure generates a transmission resonance spike of very narrow bandwidth in the photonic band gap of the device. This transmission resonance spike has a very narrow resonance frequency bandwidth. Thus, a photonic signal of a similar bandwidth to the resonance frequency bandwidth and an optical frequency corresponding to the frequency location of the transmission resonance spike is delayed by a predetermined amount.
- [0052] Terminology
- [0053] For the purposes of this disclosure, the following terms are used in describing the present invention:
- [0054] “Photonic signals” refer to electromagnetic signals, including, but not limited to, optical signals, x-ray signals, and microwave signals. Photonic signals are described either in terms of their in-air wavelength (λ) or their photonic signal frequency (ω), where $\lambda=c/(2\pi\omega)$.
- [0055] “Photonic signal delay device” refers to any device that imparts a temporal delay on a photonic signal traveling therethrough.
- [0056] “Uniform photonic band gap (PBG) structure” refers to a dielectric or semiconductor structure or fiber grating with alternating layers of material or sections of similar thicknesses having different indices of refraction periodically spaced on a substrate or along a fiber or waveguide. This type of structure is referred to, for example, as a “PBG structure” or a band-edge delay line device (See Scalora, et al., “Ultrashort pulse propagation at the photonic

band edge: large tunable group delay with minimal distortion and loss,” Phys. Rev. E Rapid Comm. 54(2), R1078-R1081 (August 1996) (incorporated by reference herein in its entirety). The word “uniform” describes the uniform periodical spacing of alternating layers or sections of similar thicknesses on a substrate or along a fiber. In addition, the term “uniform” distinguishes the conventional PBG structure, such as the band-edge delay line device described with respect to FIG. 1A, from the Fabry-Perot delay line device of the present invention.

[0057] “Fabry-Perot delay line device” refers to a PBG structure having at least one periodicity defect region interposed between periodically spaced alternating layer regions or sections in a semiconductor or fiber grating structure, according to the present invention.

[0058] “Periodicity defect” refers to a break in the periodicity of alternating refractive material layers or sections.

[0059] Example Environment

[0060] Before describing the present invention in further detail, it is useful to describe an example environment in which the invention can be implemented. The present invention can be implemented in any system utilizing optical signals. The present invention is particularly helpful in communications systems that require the synchronization of optical signals generated from a variety of sources and locations. The present invention allows a degree of design flexibility with respect to the amount of delay imparted on the signals and also with respect to the optical frequency of the signal traveling through the device. This flexibility in the design of the photonic delay structures will allow a user to implement this invention in a variety of settings.

[0061] The present invention is described in terms of this example environment. Description in these terms is provided for convenience only. It is not intended that the invention be limited to application in this example environment. In fact, after reading the following description, it will become apparent to a person skilled in the relevant art how to implement the invention in alternative environments.

[0062] Band-edge Delay Line Devices

[0063] FIG. 1A is a schematic representation of a uniform PBG structure that can impart a predetermined photonic delay having a relatively limited duration as compared to the present invention. This type of device is also referred to as a band-edge delay line device. Device 102 receives photonic signals 104 of a predetermined frequency ω and a predetermined bandwidth $d\omega$ at the entrance interface 106. Device 102 comprises a stack of alternating layers 108 and 110 of refractive materials having predetermined indices of refraction n_1 and n_2 , and predetermined thicknesses a and b , respectively. For example, first layer 108 can be designed to have a thickness (a) corresponding to the predetermined wavelength of the incoming photonic signal (λ), determined by the equation $a=\lambda/4n_1$. Similarly, second layer 110 can have an index of refraction n_2 , and a thickness (b), where $b=\lambda/4n_2$. This pattern can be repeated for N periods 122, where a period is equal to one set of alternating layers 112.

[0064] Photonic signal delay can be determined as a function of the number of periods (N) 122 chosen and the characteristic photonic band gap transmission profile seen in FIG. 2, which is described below. This type of PBG struc-

ture is also known as a distributed Bragg reflector (DBR) and is typically used as a highly reflecting mirror in laser devices.

[0065] FIG. 1B is a diagram of a characteristic index of refraction square-wave pattern profile of a uniform PBG structure for N periods. Diagram 150 plots the index of refraction (n) 152 of a uniform PBG structure as a function of distance (z) 154, which is limited by the number of periods 156 in the device. Diagram 150 illustrates the periodic nature of the abrupt refractive index changes occurring in the material. This abrupt change or discontinuity in the index of refraction of the material can be used to create photonic delay effects.

[0066] FIG. 2A displays a characteristic transmission profile 204 for a band-edge delay line device 202. Typically, the uniform PBG structure associated with device 202 exhibits an infinite number of photonic band gaps and band edges. Transmission profile 204 is a plot of such a representative photonic band gap. Transmission profile 204 is obtained by plotting the optical transmission 206 of device 202 as a function of frequency (ω) 208. The maximum possible transmission 210 of the device is 1, which corresponds to all of the input photonic signal being transmitted through the device.

[0067] Transmission curve 205 undergoes a series of relative maxima and minima depending on the frequency ω of the input photonic signal. The photonic band gap 212 corresponds to the low transmission region of the profile. The maximum in transmission occurs at the photonic band edge 213. The band-edge delay line device can be designed so that the frequency corresponding to the photonic band edge 213 matches the center frequency ω of the input photonic signal. In addition, the photonic band-edge transmission resonance bandwidth ($\delta\omega$) 214 can be designed to be at least as wide as the bandwidth $d\omega$ of the photonic signal in order to insure that the input photonic signal is not significantly distorted by the photonic signal delay device, whose pulsewidths are arbitrary in duration. Specifically, these devices can be designed to impart photonic delays on signals whose pulsewidths are on the order of picoseconds (ps) or less.

[0068] Band-edge delay line device 202 operates as a photonic delay line because at every place in the band structure that there is a maximum in the transmission function, there is a corresponding minimum in the group velocity: hence, the smaller the group velocity, the larger the photonic delay. This principle is graphically illustrated in FIG. 2B. FIG. 2B shows a graph 250 where both the transmission curve 258 (solid-line) and the group velocity (v_g) curve 262 (dashed-line) are plotted as a function of frequency (ω) 254. The transmission 252 of the input photonic signal is inversely related to the photonic signal's group velocity v_g 256 as it travels through the band-edge delay line device 202. Graph 250 demonstrates that when the signal undergoes a maximum in transmission, such as at the photonic band-edge 261, the signal's group velocity v_g is at a corresponding minimum 262. In practical terms, device 202 operates as a photonic signal delay line in that not only is the input photonic signal delayed substantially, but the light is maximally transmitted at the predetermined frequency ω .

[0069] FIGS. 3A and 3B illustrate a photonic signal delay generated by band-edge delay line device 202. FIG. 3A

shows a schematic representation of a photonic signal delay experiment 302. First, a picosecond (ps) pulse 304, having a center frequency ω and a bandwidth $d\omega$ is directed towards a bulk material 306 that does not contain a stack of alternating layers of refractive materials having varying indices of refraction. Output signal 310 is then measured at some predetermined time (T) after being transmitted through the bulk material 306. The position in distance of output signal 310 after the time T is measured at a point in space z_0 . Next, another ps pulse is delivered to band-edge delay line device 308 described in detail above. After a time T , this output signal 312 has a measured position in space corresponding to z_1 . Thus, the photonic delay 314 imparted by band-edge delay line device 308 is the measured difference $z_0 - z_1$.

[0070] FIG. 3B shows a graph 315 that illustrates the delay imparted by band-edge delay line device 308 in terms of signal intensity 316 as a function of distance traveled (z) 318 over a time T . Graph 315 plots the photonic signal delay (δ) 324 between the control photonic signal 320 (dashed-line), which traveled through bulk material 306, and the delayed photonic signal 322 (solid-line), which traveled through band-edge delay line device 308, when both are measured at a time T . Additionally, graph 315 demonstrates that band-edge delay line device 308 sufficiently preserves signal quality in terms of signal intensity 316 and pulse shape when comparing delayed signal 322 to control photonic signal 320. Because input pulse 304 has a sufficiently narrow bandwidth, all the frequency components of the pulse will have nearly the same group velocity (v_g), thereby avoiding any breakup or spreading of the pulse as it travels through band-edge delay line device 308. The net effect of the band-edge delay line device 308 on the photonic pulse is solely the delay, since there are no significant shaping effects taking place.

[0071] Fabry-Perot Delay Line Devices

[0072] In order to create a useful device for photonic delay in an optical system, an important parameter to maximize is the ratio (δ/L), where δ is the delay imparted by the PBG structure, and L is the length of the PBG structure. One known method of increasing photonic signal delay is to increase the number of periods (N) contained in a uniform photonic band gap structure. However, by increasing N , one simultaneously increases L , thereby failing to maximize the important δ/L ratio.

[0073] Interposed Periodicity Defect in a Semiconductor Structure

[0074] The present invention is directed towards maximizing the δ/L ratio by interposing a periodicity defect region into a uniform PBG structure. The periodicity defect causes a transmission resonance in the center of the photonic band gap, and thus increases δ dramatically without increasing L . This phenomenon is illustrated in FIGS. 4A and 4B.

[0075] FIG. 4A is a schematic representation of a Fabry-Perot delay line device 406 according to one embodiment of the present invention. Device 406 receives photonic signal 404 of a predetermined frequency ω and a predetermined bandwidth $d\omega$ at entrance port 405. Device 406 comprises at least two stacks (or regions) 420 and 422 of alternating layers 408 and 410 of refractive materials having predetermined indices of refraction n_1 and n_2 , and predetermined thicknesses (a) 414 and (b) 416, respectively. In the center

of the Fabry-Perot delay line device **406**, a periodicity defect region **412** is interposed between two stacks **420** and **422**, with each stack having an equal number of alternating layers of refractive material. Periodicity defect region **412** is also a refractive material having an index of refraction (n) that is equivalent to either n_1 or n_2 . As mentioned previously, the term "defect", in this context, simply means a break in the periodicity of the structure. The thickness (c) **418** of periodicity defect region **412** is designed to be different than thicknesses a and b . For example, if layer thicknesses in the uniform stacks **420**, **422** are taken to be one quarter-wavelength long, then the thickness of periodicity defect region **412** can be one half or one wavelength in thickness. However, other thicknesses for periodicity defect region **412** can be utilized, although only certain arrangements will maximize both transmission and delay at the same time. As the signal travels through the Fabry-Perot delay line device **406**, a predetermined delay δ is imparted on the photonic signal, resulting in a delayed output photonic signal **426**.

[**0076**] For example, in one embodiment of the present invention, a photonic signal **404** of in-air wavelength λ is delivered to Fabry-Perot delay line device **406**. Layer **408** is a layer of gallium arsenide (GaAs), with an index of refraction of about 3.4 and a thickness (a) given by $a=\lambda/4n_1$. Layer **410** is a layer of aluminum arsenide (AlAs), with an index of refraction of about 2.9 and a thickness (b) given by $b=\lambda/4n_2$. Periodicity defect region **412** in this embodiment is a layer of GaAs, with a thickness (c) **418** of about λ . It should be noted that this type of structure is not limited to using only AlAs and GaAs periodic layers: other commonly known semiconductor materials such as indium arsenide (InAs), for example, can be also utilized in this structure, depending on the delay requirements of the user. Additionally, in one preferred example, thickness c is about two to four times greater than thicknesses a or b , which results in the photonic band gap profile **450** displayed in **FIG. 4B**. Of course, the present invention is not intended to be so limited as the thicknesses a , b , or c can be different relative distances. Further, instead of a semiconductor structure, another possibility includes the use of optical fiber or waveguide gratings to create photonic delay. A photonic delay device based on an optical fiber grating is described in detail below.

[**0077**] The interposition of periodicity defect region **412** creates a characteristic photonic band gap which is displayed in **FIG. 4B**, described in detail below. Fabry-Perot delay line device **406** is designed to alter incident photonic signals **404** only in terms of temporal delay: no shaping or pulsewidth characteristics are significantly altered.

[**0078**] The present invention represents a significant improvement over the state of the art in terms of photonic signal delay (δ); for the same number of periods (N) in a Fabry-Perot delay line device, the δ created can be at least an order of magnitude greater in the invention than in a band-edge delay line device (with no periodicity defect interposed). In practical terms, the present invention allows for an improved device with a length (L) equivalent to the length of band-edge delay line devices, but with a much larger δ .

[**0079**] The physical principle giving rise to this dramatic increase in the photonic delay is illustrated in **FIG. 4B**. Transmission profile **450** of Fabry-Perot delay line device

406 is plotted in terms of photonic signal transmission **452** as a function of frequency (ω) **454**. Device **406** is referred to as a Fabry-Perot delay line device because the corresponding transmission resonance is usually found in Fabry-Perot resonators, well known to those skilled in the art. Transmission curve **456** undergoes a similar series of relative maxima and minima previously seen for the band-edge delay line device illustrated in **FIG. 2A**. The transmission curve **456** (solid-line) for device **406** also contains a relative transmission maximum at the photonic band-edge **458** that was also seen for the band-edge delay line device of **FIG. 2A**. Unlike **FIG. 2A**, however, a new transmission resonance peak **462** (dashed-line) is created at the center of the photonic band gap **460** as a result of the interposition of periodicity defect region **412**. Fabry-Perot delay line device **406** can be designed so that the frequency corresponding to transmission resonance peak **462** matches the center frequency ω of photonic signal **402** (where, $\lambda=c/(2\pi\omega)$) to impart the maximum predicted photonic signal delay.

[**0080**] In general, the improvement in delay δ caused by the Fabry-Perot delay line device of the present invention is based on the narrower transmission resonance peak bandwidth $\delta\omega_1$; where $\delta\omega_1 \sim \delta\omega/10$ to $\delta\omega/100$, and $\delta\omega$ is the frequency bandwidth of the photonic band-edge **459**. Since $\delta\omega_1$ is narrower than $\delta\omega$, the frequency bandwidth of the input photonic signal ($d\omega$) must also be narrower to avoid beam distortion. This bandwidth requirement necessitates an increase in the photonic signal pulsewidth delivered to the Fabry-Perot delay line device of the present invention. For example, instead of delivering a picosecond (ps) pulse to the Fabry-Perot delay line device, the present invention is best utilized in a system where nanosecond (ns) pulses are sought to be delayed.

[**0081**] It should be noted that the above periodicity defect structure represents only one embodiment of the invention. One of the important aspects of the present invention is the flexibility to create a desired delay. For example, there is no particular restriction to work around the one-quarter wavelength periodicity of the alternating layers. In addition, the interposed periodicity defect region does not have to be larger than the alternating layer thicknesses nor is it required to be placed in the center of the structure. While manufacturing considerations may make a one wavelength or a one-half wavelength periodicity defect preferable over another thickness, there are no physical reasons why other thicknesses can not be attempted. Further, the placement of a periodicity defect region is not restricted to only the center of the delay device; a periodicity defect region can be placed at many different locations in the delay device, depending on the type of photonic delay desired. Fundamentally, as long as there is a break in the periodicity of the structure, the transmission resonance spike will appear at some location in the photonic band gap of the structure.

[**0082**] **FIG. 5** graphically illustrates the improvement in photonic signal delay created by the present invention. Graph **502** plots photonic signal delay **504** as a function of the number of periods (N) **506** within a band-edge delay line device **508** (curve (a), solid-line) and a Fabry-Perot delay line device **510** (curve (b), dashed-line) such as that described in **FIG. 4**. While curve (a) **508** follows an N^2 dependence, curve (b) **510** represents a steeper, $N^2 \cdot e^N$ dependence. As a result, according to the present invention,

a significantly greater photonic signal delay is obtained as compared to a band-edge delay line device.

[0083] For example, a Fabry-Perot delay line device similar to device 406 described above was fabricated and tested. The Fabry-Perot delay line device comprised a total of 40 periods of GaAs/AlAs alternating layers grown on a GaAs substrate. In order to maximize the transmission from the structure to unity, a one-wavelength defect layer was introduced 18 periods from the surface, and 22 periods from the substrate. Actual measured delay was approximately 10 ps. Thus, the delay-to-device-length ratio was improved by approximately a factor of 20 over a band-edge delay line device, such as band-edge delay line device 102 described above.

[0084] Multiple Periodicity Defects

[0085] According to a second embodiment of the present invention, a Fabry-Perot delay line device is designed to impart predetermined delays on two photonic signals having different frequencies that travel through the device. FIG. 6A is a schematic representation of a second embodiment 603 of the present invention: a Fabry-Perot delay line device with at least two periodicity defect regions. Device 602 receives photonic signals 603 and 604 of different signal frequencies ω_1 and ω_2 , respectively, and a predetermined bandwidth $\Delta\omega$ at entrance port 605. Device 602 comprises at least three stacks (or regions) 616, 618 and 620 of alternating layers 606 and 608 of refractive materials having predetermined indices of refraction n_1 and n_2 , and predetermined thicknesses (a) 626 and (b) 628, respectively. Two separate periodicity defect regions 610 and 612 are interposed in separate locations between the three stacks 616, 618 and 620, with each stack having an equal number of alternating layers of refractive material. Periodicity defect regions 610 and 612 are also refractive materials respectively having indices of refraction n_3 and n_4 , that can be the same as either n_1 or n_2 . The thicknesses (c) 622 and (d) 624 of the periodicity defect layers 610 and 612 are designed to be greater than the thicknesses a and b. In addition, periodicity defect layers 610 and 612 can be of equal thickness or of differing thickness, depending on the desired transmission resonances. As signals 603 and 604 travel through the delay device 602, a predetermined delay δ_1 can be imparted on the photonic signal 603, and a second predetermined delay δ_2 can be imparted on the photonic signal 604, resulting in delayed output photonic signals 614 and 615.

[0086] Transmission profile 650 is shown in FIG. 6B. This graph represents the transmission profile of the second embodiment of the present invention, Fabry-Perot delay line device 602. FIG. 6B plots photonic signal transmission 652 as a function of frequency (ω) 653. Transmission curve 656 undergoes a similar series of relative maxima and minima as previously seen in FIG. 2B. While the transmission curve 656 (solid-line) for Fabry-Perot delay line device 602 contains a relative transmission maximum at the photonic band-edge 659 that was also seen for the device of FIG. 4A, two transmission resonance peaks 660 and 662 (dashed-lines) are now created about the center of the photonic band gap 460 as a result of the interposition of the two periodicity defect regions 610 and 612. These separate resonance peaks 660 and 662 occur at frequencies ω_1 and ω_2 , respectively. In order to best utilize delay device 602, it can be designed so that the frequencies corresponding to transmission reso-

nance peaks 660 and 662 match the frequencies ω_1 and ω_2 of photonic signals 603 and 604 in order to impart the maximum delay on each optical signal.

[0087] As described above, the present invention provides the user with the flexibility of controlling the delay imparted by the Fabry-Perot delay line device by choosing an appropriate set of delay parameters. The user can control the location of the transmission resonance spikes and the input frequencies of the photonic signals. For example, one periodicity defect region can have a thickness on the order of $\lambda/2$, and a second periodicity defect region can have a thickness on the order of λ , where λ corresponds to the optical in-air wavelength of the photonic signal(s) delivered to a Fabry-Perot delay line device, such as device 602. This arrangement generates separate transmission resonance spikes in the photonic band gap and, thus, can be used to pass two different frequencies of light. In one embodiment, the two periodicity defect regions can be placed in a PBG structure so that their positions are symmetric: the corresponding resonance spikes will also be symmetrically positioned about the center of the band gap. However, these periodicity defect regions do not have to be placed symmetrically within a PBG structure. In addition, the invention does not require that there be an equal number of alternating layers on either side of the periodicity defect regions, or that the number of periodicity defect regions be limited to only two. Different relative layer thickness and different numbers of layers will be apparent to one skilled in the art given this description.

[0088] Variable Photonic Signal Delay

[0089] A third embodiment of the present invention is illustrated in FIG. 7. A tunable laser source 704 delivers various photonic signals via a fiber optic cable 706 to Fabry-Perot delay line device 708. These delayed signals can then be launched into a communications network 710 in synchronization with other photonic signals. Since a tunable laser source is capable of generating photonic signals that comprise a range of photonic frequencies, using the Fabry-Perot delay line device will impart varying photonic delays depending upon the frequency of the input photonic signals.

[0090] The embodiments described above represent the invention being used as a passive device, in which no voltage, bias current, or electromagnetic field is applied to the Fabry-Perot delay line device. However, a voltage can be applied to one or more defect regions of a Fabry-Perot delay line device to vary the index of refraction of the respective periodicity defect regions which comprise the structure. By varying the index of refraction of the periodicity defect regions, the delay imparted on the input photonic signals can be varied. This embodiment of the present invention is illustrated in FIG. 8, which displays a schematic of Fabry-Perot delay line device 802 connected to a voltage source 816. The power supply can apply a positive 812 or negative 814 voltage to the periodicity defect region of the structure at electrical contacts 804. By changing the voltage applied to the periodicity defect region 810, the index of refraction of region 810 changes. As a result, device 802 can thereby impart a varying photonic delay on the photonic signals passing therethrough.

[0091] Fiber Grating Photonic Delay Devices

[0092] According to a further embodiment of the present invention, optical fiber or waveguide gratings are also used

to create photonic delay. Optical fiber gratings are similar to the types of PBG structures described above in that they are also periodic structures. The index of refraction for a fiber grating can achieve an index modulation depth (i.e., a high and low value) similar to that of high index contrast semiconductor structures. However, fiber gratings are structures with a smaller index discontinuity than that associated with a semiconductor PBG structure: for a fiber grating an index modulation along its core is typically on the order of $\delta n = 10^{-3}$ to 10^{-4} , as opposed to a semiconductor PBG structure with an index modulation approaching unity. Since the bandwidth of transmission resonances and band gaps are proportional to δn (the index modulation depth), fiber grating delay devices are preferred for use with optical pulses of longer (i.e., nanosecond) duration in order to preserve their shape.

[0093] A fiber grating can be created on an optical fiber by well-known fabrication techniques. For example, see the fiber grating applications and fabrication techniques described in "Continuously tunable single-mode erbium fiber laser," by G. Ball and W. Morey, *Optics Letters*, Vol. 17, No. 6, p.420 (1992) and "Spatially-multiplexed fiber-optic Bragg grating strain and temperature-sensor system based on interferometric wavelength shift," by Y. Rao, et al., *Electronics Letters*, Vol. 31, No. 12, p. 1009 (1995), which are both incorporated by reference in their entirety herein.

[0094] For example, fiber grating fabrication can be accomplished by placing an optical "mask" over a photo-sensitive fiber core and then by illuminating the mask-fiber assembly with a high intensity ultraviolet light beam, such as an Excimer laser. The resulting grating, referred to as a fiber grating, displays much the same properties of a high index contrast semiconductor PBG structure, especially with respect to band gaps and transmission resonances. In addition, a mask can be designed to create a grating which imparts either a band-edge delay line effect or a Fabry-Perot delay line effect.

[0095] According to one example embodiment of the present invention, a fiber grating photonic delay device comprises alternating sections having different indices of refraction periodically spaced along the fiber or waveguide. According to another example embodiment of the present invention, the fiber grating photonic delay device can comprise a periodicity defect region interposed between the regions of alternating sections. Thus, the fiber grating photonic delay device operates according to the same physical principles that apply to the semiconductor band-edge and Fabry-Perot devices described above: the periodic nature of the abrupt refractive index changes caused by the grating occurring in the material can be used to create photonic delay effects. When an electromagnetic field is applied to the fiber core with the mask, the index of refraction is changed in the portion of the fiber that is exposed to the illumination. In other words, once the field enters the fiber core it permanently alters the refractive index of that region. Thus, the fiber device consists of sections where the index of refraction is altered and sections where the refractive index is unchanged. The spacing of these alternating refractive index sections can be based on one-quarter wavelength section thicknesses such as those described for the above band-edge delay line device. Alternatively, the periodic nature of the spacings can be broken, with one or more periodicity defect regions interposed, depending on the

delay required, similar to the Fabry-Perot delay line devices described above. For example, two or more regions of the fiber grating can comprise sections that periodically alternate proportional to the in-air wavelength λ of the incoming optical signal in order to maximize both transmission and delay. A periodicity defect region of a different optical path length can be interposed between these two regions of alternating sections, resulting in a transmission resonance similar to those described above.

[0096] As mentioned earlier, a PBG structure can also be used as a variable photonic delay device. However, in the case of a fiber grating, the location of a Fabry-Perot resonance can be changed in the frequency domain, and hence tuned by piezo-electric means, as opposed to electro-optic means. That is, a voltage can be applied to the defect region, as shown in **FIG. 8**, in the fiber grating embodiment of the present invention not to cause a change in index of refraction, but rather to cause slight pressure to be applied in the periodicity defect region. The pressure, in turn, causes a slight elongation (or physical stretching) of the periodicity defect region, and hence a change of its optical path. This method is thus equivalent to modifying the refractive index by electro-optic means, leading to a variable photonic delay.

[0097] Defect Layer Doped with a Gain Medium

[0098] An embodiment of the present invention includes a defect layer doped with a gain medium. An increase in the density of modes essentially means that the density of photons increases at a particular frequency. This increase can be accomplished by utilizing a defect layer that is doped with a gain medium. The introduction of gain automatically causes an increase in the photon density, and therefore, a narrowing of the density of modes. This allows tuning of the group velocity, just as if periods were being added.

[0099] There are several advantages to this scheme. First, once a structure including a defect layer doped with a gain medium is built, the maximum delay can simply be modified by changing the structure's gain. Second, since this scheme does not alter delay by tuning a field across a structure's resonance, there is no loss of signal. On the contrary, the signal is amplified. Absorption (which represents negative gain) can also be used to tune the group velocity, although the transmitted signal may in this case be reduced.

[0100] **FIG. 9** depicts a structure **900** grown on a GaAs substrate. Structure **900** includes at least two stacks (or regions) **902** and **906** of alternating layers of refractive materials. The alternating layers in stack **902** have predetermined indices of refraction n_1 and n_2 . The alternating layers in stack **906** have predetermined indices of refraction n_3 and n_4 . The alternating layers in stacks **902** and **906** have predetermined thicknesses (a) **910**, (b) **912**, (c) **914**, and (d) **916**, respectively. In the center of the structure **900**, a periodicity defect region **904** is interposed between stacks **902** and **906**. As illustrated in **FIG. 9**, stack **902** comprises 18 periods of alternating GaAs and AlAs layers. However, stack **906** comprises 22 periods of alternating GaAs and AlAs layers. Periodicity defect region **904** is a GaAs cavity having a one wavelength thickness **918**. As mentioned previously, the term "defect", in this context, simply means a break in the periodicity of the structure. Structure **900** receives a photonic signal **920** of a predetermined frequency ω and a predetermined bandwidth $\delta\omega$ at an entrance port **922**. As photonic signal **920** travels through structure **900**, a

delay d is imparted on photonic signal **920**, resulting in a delayed output photonic signal **924**.

[0101] This configuration creates a sharp transmission resonance with a full width at half maximum of $\delta\lambda=0.34$ nm in the middle of the photonic band gap, at $\lambda=1550$ nm, and maximizes the transmission to unity. The properties of this transmission resonance inside the gap are similar to the properties of the photonic band edge resonances, except for the location of the transmission resonance, and the magnitude of the group velocity, or group index, at the defect mode, which is about two orders of magnitude larger than the group index of the band edge delay line discussed above.

[0102] For structure **900**, the maximum group index is about $N_g=300$. Due to the limited bandwidth of structure **900**, any pulse tuned at the resonance maximum, and whose duration is greater than about 100 ps or so will propagate at the group velocity of $C/300$. The physical length of structure **900** is approximately $L=10.3$ microns; taking $C=3\times 10^8$ m/sec., thereby producing a delay of approximately $d=8-10$ picoseconds.

[0103] The exploration of ways to tune delay in photonic band gap structures has led to some unexpected and interesting new results. One such result occurs when a gain medium is introduced in periodicity defect region **904**. This means that electrical or optical pumping of the Fabry-Perot (F-P) cavity (periodicity defect region **904**) is introduced. As photonic signal **920** makes its way through structure **900**, it experiences some gain, i.e., the density of photons increases. This causes photonic signal **920** to slow down further. This reduction in speed depends exponentially on the amount of gain present, as described below with reference to **FIG. 10**.

[0104] According to the present invention, periodicity defect region **904** is doped to change the absorptive and emissive properties of the original semiconductor so that the electrons of periodicity defect region **904** are excited to a higher state, thereby placing them in a position to give up that energy to photonic signal **920**. Accordingly, photonic signal **920** is amplified according to a gain. Such doping can be with beryllium atoms, carbon atoms, and/or with any other substance, as would be apparent to persons skilled in the relevant art(s).

[0105] In a doped semiconductor material, such as doped periodicity defect region **904**, there are many ways to put electrons in an excited state. One such way involves optical pumping. Optical pumping involves the injection of optical energy in a manner that excites electrons from a lower level to an upper level. Such electrons will remain at an upper level until photonic signal **920** absorbs photons from them.

[0106] Another way to put electrons in an excited state is through the injection of an electrical current. The electrical current causes the electrons to enter an excited state, until photonic signal **920** absorbs photons from the excited electrons. This approach differs from the approach described above with reference to **FIG. 8**, where a voltage is applied to periodicity defect region **810** to change its index of refraction. In contrast, applying an electrical current to doped periodicity defect region **904** produces a gain. Thus, some of the electrical current is captured in doped periodicity defect region **904** region to generate light, thereby producing gain.

[0107] **FIG. 10** is a plot **1000** of delay d as a function of the gain coefficient for structure **900**. As illustrated in **FIG.**

10, delay d of photonic signal **920** increases with the gain coefficient. As described herein, the gain coefficient increases as more energy is injected in periodicity defect region **904**. Thus, the present invention provides a mechanism that enables the tuning of gain (or loss). Accordingly, this tuning mechanism provides the ability to modulate, or change, the delay of photonic signal **920** by changing the gain of structure **900**.

[0108] It is important to note that the generic term gain can also be used to indicate absorption. That is, gain causes an increase in the density of modes, a reduction of the group velocity, and an increase in delay. On the other hand, absorption causes a reduction of the density of modes, an increase of the group velocity, and hence a decrease in delay.

[0109] This gain(or loss)-tuning mechanism for photonic signals **920**, such as nanosecond pulses, constitutes a major achievement because of the limitations involving the production of devices, such as structure **900**. One such limitation involves device geometry, which is dictated by molecular beam epitaxy (MBE) fabrication techniques. For instance, according to current MBE techniques, it is difficult to regulate the thickness of layers in structures having greater than 40 layers. Another limitation involves economics. According to some estimates, the cost to produce each layer of a structure is relatively expensive. Without the introduction of a gain medium, these limitations place constraints on the maximum delay obtainable at a reasonable cost.

[0110] However, as **FIG. 10** illustrates, the above limitations are removed by devices, such as structure **900**, or any similar or equivalent structure as would be apparent to persons skilled in the relevant art(s). For such devices, by simply introducing and modulating the maximum gain, the maximum delay can be tuned well beyond the maximum value dictated by the geometry of the device.

[0111] According to one embodiment of the present invention, ordinary vertical cavity surface emitting laser (VCSEL) diodes can be implemented as a defect layer doped with a gain medium. These devices include a gain doped defect layer as in a delay line cavity. Furthermore, VCSELs are currently available at negligible cost. The gain coefficients present in ordinary VCSELs or diode lasers can be made to equal or approximately equal the gain coefficients illustrated above with reference to **FIG. 10**.

[0112] **FIGS. 11 and 12** provide two views of a VCSEL **1100** according to the present invention. VCSEL **1100** includes two stacks **1102** and **1106** of alternating layers of refractive materials, each layer having predetermined indices of refraction and predetermined thicknesses. In an embodiment, each stack is a quarter-wave mirror stack, where stack **1102** is 99.0% reflective and stack **1106** is 99.9% reflective. Adjacent to stack **1106** is a GaAs substrate **1108**. In the center of the structure **1100**, a periodicity defect region **1104** is interposed between stacks **1102** and **1106**. Periodicity defect region **1104** is doped with a gain medium. In an embodiment, this doping comprises three quantum wells **1110a-1110c**. This doping is performed in such a way that when a current is injected in periodicity defect region **1104**, atoms go to an excited state, and give up a photon when returning to the ground state. Such an injection of current creates gain. Accordingly, when a photonic signal **1112** at a predetermined frequency ω and bandwidth $d\omega$ is

input to an entrance interface **1116**, a delayed photonic signal **1114** results. The magnitude of this delay varies according to the amount of electrical current injected in periodicity defect region **1104**.

[**0113**] **FIG. 12** illustrates a second view of VCSEL **1100**. In addition **FIG. 12** illustrates the injection of an electrical current **1202** into VCSEL **1100**. The gain of VCSEL **1100** is controlled by modulating electrical current **1202** (as indicated by the arrow). The power output of VCSEL **1100**, and hence its gain, is proportional to electrical current **1202**. Thus, the velocity of photonic signal **1112** is controlled by modulating electrical current **1202**. Accordingly, as electrical current **1202** increases, the velocity decreases. A decrease in velocity causes an increase in delay of the input pulse.

[**0114**] According to the present invention, the injection of electrical current in VCSEL **1100** causes lasing at a particular wavelength. In an embodiment, the wavelength of photonic signal **1112** has the same wavelength.

[**0115**] A doped VCSEL structure whose initial resonance width is not too thin that it can be easily fabricated. In this embodiment, an injected external pulse laser source is input to the doped VCSEL structure.

[**0116**] In one example a VCSEL structure as described by Bouche et al. is used as a delay device according to the present invention. See Bouche et al., *Dynamics of Gain in Vertical Cavity Lasers and Amplifiers at 1.53 μm using femtosecond photoexcitation*. 73 Applied Physics Letters 2718 (Nov. 9, 1998) (hereinafter Bouche) (incorporated herein by reference in its entirety). As described in Bouche, this structure can be a 3.5λ cavity with an active medium composed of 2×9 InGaAsP strained multiple quantum wells placed at antinodes. The active medium is sandwiched between two and four pairs of Si/SiO₂ mirrors with reflectivities of 96.2% and 99.7%, respectively.

[**0117**] **FIG. 13** is a plot **1300** of the reflectance **1302** and transmittance **1304** for the passive structure described in Bouche.

[**0118**] According to one example of the invention, gain in the central part of the quantum well region is introduced in the structure described in the Bouche et al. article. An increase was observed in the transmission. **FIG. 14** is a plot of the resonance **1402** of this structure located near 1528 nm when gain is introduced. This gain causes significant narrowing of the line.

[**0119**] **FIG. 15** is a plot illustrating the propagation of the transmitted and reflected pulses **1502**, for an input pulse whose FWHM=120 fs, without gain or loss (i.e., the linear results of the Bouche structure are displayed). For comparison, a pulse **1504** that propagates in free space through a distance D =to the length of the device is also plotted.

[**0120**] **FIG. 16** is a plot illustrating the delay of a 1 ps pulse to show that it couples better with the structure, and hence the delay increases. This plot includes a reference free space pulse **1602**, a reflected pulse **1604**, and a delayed transmitted pulse **1606**.

[**0121**] **FIG. 17** is a plot illustrating the delay of a 10 ps input pulse. This plot includes a reference free space pulse **1702**, a reflected pulse **1704**, and a delayed transmitted pulse **1706**.

[**0122**] **FIG. 18** is a plot illustrating the delay of a 5 ps input pulse when the Bouche structure is doped with a gain material. This plot includes a delayed transmitted pulse **1802** and a reflected pulse **1804**.

[**0123**] **FIG. 19** is a plot illustrating the delay of a 5 ps input pulse without the addition of a gain material to the Bouche structure. This plot includes a transmitted pulse **1902** and a reflected pulse **1904**. As indicated in **FIG. 19**, the delay obtained is less than in **FIG. 18**.

[**0124**] Accordingly, the present invention includes a method of imparting a delay to an input photonic signal of a predetermined frequency and a predetermined bandwidth. In one embodiment, the semiconductor structure is a photonic band gap structure having a defect layer doped with a gain medium, such as structure **900**. In a further embodiment, the semiconductor structure is a VCSEL, as illustrated in **FIGS. 11 and 12**. In other embodiments, the structure can be a structure that exhibits a photonic band gap structure.

[**0125**] This method includes the steps of sending the input photonic signal along an optical path; passing the photonic signal through a first region of periodically alternating refractive sections in said optical path of the photonic signal; passing the photonic signal through a periodicity defect region in said optical path, where the defect region is doped with a gain medium and excited by an energy source; and passing the photonic signal through a second region of periodically alternating refractive sections in said optical path. The energy source can be electrical current, a second photonic signal such as a continuous wave signal having the same frequency as the input photonic signal, mechanical energy such as force and/or pressure, and/or thermal energy.

[**0126**] Conclusion

[**0127**] Thus, the invention recognizes that the group velocity of the probe pulse can be controlled by adjusting the gain or absorption present in a photonic band gap structure. When gain is dominant, such as when an input pulse is tuned to the low frequency band edge resonance, the pulse group velocity decreases. When loss is present, such as when an input pulse is tuned to the high frequency band edge resonance, the group velocity of the pulse increases.

[**0128**] Embodiments of the present invention can include any number of periodic stacks and periodicity defect regions. In such embodiments, periodic stacks can be doped with gain media. Also, in embodiments including multiple periodicity defect regions, any number of them can be doped with a gain medium in any combination.

[**0129**] While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. It will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined in the appended claims. Thus, the breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

What is claimed is:

1. A device for delaying a photonic signal by a predetermined delay, the photonic signal having a predetermined frequency and a predetermined bandwidth, comprising:

- a first region having periodically alternating refractive material layers which exhibit a photonic band gap structure, said first region comprising a first refractive material layer having a first thickness and a first index of refraction, and a second refractive material layer having a second thickness and a second index of refraction;
- a second region having periodically alternating refractive material layers which exhibit a photonic band gap structure, said second region comprising a third refractive material layer having a third thickness and a third index of refraction, and a fourth refractive material layer having a fourth thickness and a fourth index of refraction;
- a periodicity defect region, interposed between said first and second regions of periodically alternating refractive material layers, wherein said periodicity defect region is doped with a gain medium;

wherein the first predetermined delay is imparted to the photonic signal during passage through the device when said periodicity defect region is excited by an energy source.

2. The device of claim 1, wherein said energy source is an electrical current.

3. The device of claim 1, wherein said energy source is an optical signal having the predetermined frequency.

4. A method of imparting a delay to a photonic signal of a predetermined frequency and a predetermined bandwidth by a predetermined temporal duration, wherein the photonic signal is generated by an optical source, comprising the steps of:

sending the photonic signal along an optical path;

passing the photonic signal through a first region of periodically alternating refractive sections in said optical path of the photonic signal;

passing the photonic signal through a periodicity defect region in said optical path, wherein the periodicity defect region is doped with a gain medium and excited by an energy source; and

passing the photonic signal through a second region of periodically alternating refractive sections in said optical path.

5. The method of claim 4, wherein the energy source is an electrical current; and further comprising the step of setting the electrical current to impart the desired delay.

6. The method of claim 4, wherein the energy source is an optical signal having the predetermined frequency; and further comprising the step of setting the optical signal to impart the desired delay.

* * * * *