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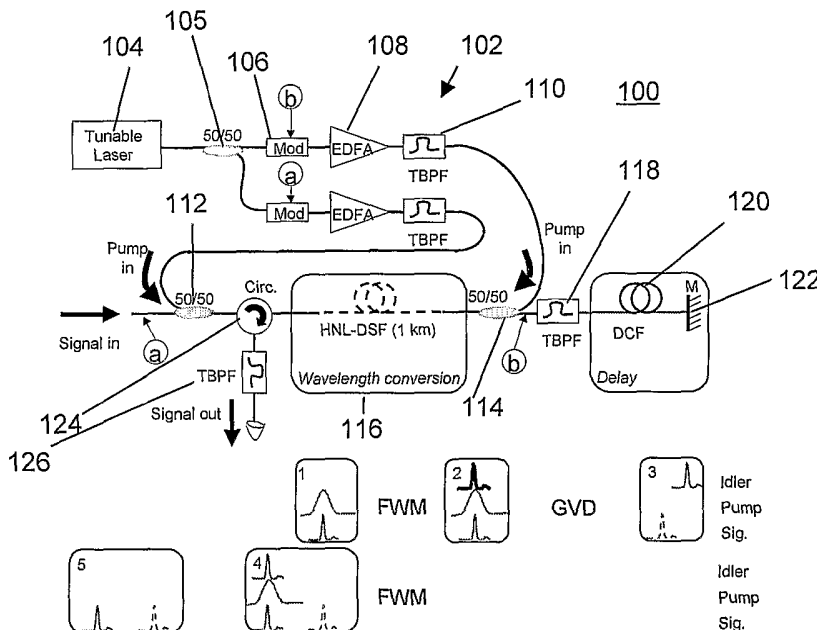
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(54) Title: ALL-OPTICAL, CONTINUOUSLY TUNABLE, PULSE DELAY GENERATOR USING WAVELENGTH CONVERSION AND DISPERSION



(57) Abstract: A technique for generating variable pulse delays uses one or more nonlinear-optical processes such as cross-phase modulation, cross-gain modulation, self-phase modulation, four-wave mixing or parametric mixing, combined with group-velocity dispersion. The delay is controllable by changing the wavelength and/or power of a control laser. The delay is generated by introducing a controllable wavelength shift to a pulse of light, propagating the pulse through a material or an optical component that generates a wavelength dependent time delay, and wavelength shifting again to return the pulse to its original wavelength.

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All-Optical, Continuously Tunable, Pulse Delay
Generator Using Wavelength Conversion and Dispersion

Cross Reference to Related Applications

[0001] This application claims the benefit, under 35 U.S.C. 119(e) of US Provisional Application No. 60/662,391, filed March 17, 2005, which is hereby incorporated by reference in its entirety. US Application No. 11/123,224, which was filed on May 6, 2005 and is commonly owned with the subject application, discloses subject matter that is related to the subject matter of this application.

Government Sponsorship Statement

[0002] This invention was made with Government support from the US Department of the Air Force under Contract No. F49620-03-1-0223. The Government has certain rights in the invention.

Background of the Invention

1. Field of the Invention

[0003] The present invention relates in general to a continuously tunable optical pulse delay generator that employs a combination of group velocity dispersion and wavelength conversion to achieve a variable delay.

2. Description of the Background Art

[0004] Devices that allow for tunable optical pulse delays are of central importance to numerous fields including optical coherence tomography, ultrafast pulse metrology, radio frequency communications and optical communications. Given the tremendous variety of applications and settings where optical pulse delays are used, it is critical to have a variety of approaches for generating them. Currently there exist several options. The most straightforward approach uses bulk beam splitters and mechanical translation, forcing pulses to traverse a physical length that can be varied in a continuous fashion. The technique can be improved upon by using a resonant structure, such as a Bragg grating or microresonator, so that the pulses traverse the same length many times. Recent advances in fiber Bragg grating design and device packaging have resulted in the demonstration of tunable devices where one varies the group delay by either varying the wavelength of light or by physically changing the period of the grating. Using a fast device to switch pulses out of a recirculating loop is a good way to generate discretely variable delays. Each of the approaches described above has benefits and drawbacks in terms of maximum delay, accuracy of delay, wavelength of operation, speed of operation, pulse distortion, and conceptual complexity.

Summary of the Invention

[0005] The present invention relates to a novel technique for generating variable pulse delays (both positive and negative since the invention can also be used for pulse advancement) that uses one or more linear or nonlinear-optical processes such as cross-phase modulation, cross-gain modulation, self-phase modulation, four-wave mixing or parametric mixing, combined with group-velocity dispersion. The delay is controllable by changing the wavelength and/or power of a control laser. In all embodiments of the invention, the delay is generated by introducing a controllable wavelength shift to a pulse of light, propagating the pulse through a component, such as a dispersive fiber, that generates a wavelength dependent time delay and wavelength shifting again to return the pulse to its original wavelength. Residual pulse distortion can be eliminated by using a compensating fiber or diffraction grating. The change in delay that a pulse experiences is proportional to the wavelength shift that was introduced times the group-velocity dispersion of the dispersive fiber, where the shift can be varied by tuning the wavelength of the pump laser.

[0006] A number of preferred embodiments of the invention are disclosed herein. In one preferred embodiment, an all-optical Sagnac interferometer is employed, which includes a ring of optical fiber sections, including: a first wavelength conversion section, which can be a highly-nonlinear dispersion-shifted fiber (HNL-DSF); a dispersive or delay section, which can be a span of dispersion compensating fiber (DCF); and a second wavelength conversion section, which can also be HNL-DSF. A second embodiment also employs the same sections of optical fibers, but arranged in a retroreflecting configuration wherein the pulses are reflected for a second pass through the fiber sections. In a third preferred embodiment, wavelength conversion is accomplished using a fiber-optic parametric amplifier (FOPA). In this embodiment, signal pulses from a tunable pumped, optical-parametric oscillator system are amplified within a span of HNL-DSF, which results in the generation of idler pulses that are spectrally shifted according to $2\omega_p = \omega_s + \omega_i$ where ω_p , ω_s , and ω_i are the angular frequencies of the pump, signal and idler pulses, respectively. After emerging from the HNL-DSF, the idler pulses propagate forward and back through a span of DCF. The temporal delay that the idler pulses acquire is proportional to the original wavelength shift times the group-velocity dispersion coefficient of the DCF. The idler pulses are then spectrally shifted back to the original signal wavelength using parametric amplification in the reverse direction through the HNL-DSF.

[0007] The subject invention combines several key innovations that make it much more flexible and useable than other controllable optical delay devices. Probably the most notable

of these innovations is the fact that the delay is generated by using an all-optical process such as cross-phase modulation, cross-gain modulation, four-wave mixing, and/or parametric mixing. As the phrase implies, "all-optical" simply means that the various components employed to implement the delay generator are purely optical devices that operate through interaction of one beam of optical radiation with another beam of optical radiation. This is in contrast to electro-optical devices, for example, which employ electric signals to control beams of optical radiation.

[0008] Other notable innovations or key features of the invention include the following: the delay is continuously tunable by changing the wavelength and/or power of the pump laser; the system can generate gain or amplification in addition to delay; as noted above, the system can be configured to generate pulse advancement (i.e. negative delay) as well as delay; the system preserves phase information present in the signal pulse train; the use of large wavelength shifts (1 nm – 200 nm) results in large tunable delays such that the delay can be large relative to the initial signal pulse width; and the system complexity is dramatically reduced by using common-path (i.e., Sagnac, or retroreflecting) configurations. The relative pulse delay can be made large (on the order of 1000 nanoseconds) or small (on the order of 10 femtoseconds), depending upon the delay range and sensitivity desired. At the same time, the output signal wavelength is the same as that of the input, and the delay-to-pulse-width ratio can be greater than 1000.

Brief Description of the Drawings

[0009] The features and advantages of the invention will become apparent from the following detailed description of a preferred embodiment thereof, taken in conjunction with the accompanying drawings, in which:

[0010] FIG. 1 is a schematic of an all-optical delay generator that is constructed in accordance with a first preferred embodiment of the present invention and employs a Sagnac interferometer;

[0011] FIG. 2 is a schematic of an all-optical delay generator that is constructed in accordance with a second preferred embodiment of the present invention and employs a linear, retroreflecting configuration;

[0012] FIG. 3 is a schematic of a continuously tunable all-optical delay generator constructed in accordance with a third preferred embodiment that employs a fiber-optic parametric amplifier (FOPA);

[0013] FIG. 4A is a graph showing the experimental results obtained using the FOPA based all-optical delay generator of FIG. 3. Plotted on the left axis are the measured (points)

along with a linear fit (line) where delays of 800 ps have been demonstrated. Plotted on the right axis is the expected parametric gain as a function of pump wavelength;

[0014] FIG. 4B is a graph showing the corresponding measured temporal traces, as recorded with a 10-GHz detector, of signal pulses for the data points shown in FIG. 4A; and

[0015] FIG. 5 is a graph showing measured optical spectra for the signal pulses at the input (solid line) and output (dot-dash line) of the delay generator of FIG. 3.

Detailed Description of the Invention

[0016] As already noted, the present invention uses one or more linear or nonlinear-optical processes such as cross-phase modulation, cross-gain modulation, four-wave mixing or parametric mixing, combined with group-velocity dispersion for generating variable pulse delays. The delay is controllable by changing the wavelength and/or power of a control laser. FIGs. 1-3 illustrate 3 possible embodiments of such a device, each of which is an "all-optical" delay generator.

[0017] With reference first to FIG. 1, an all-optical delay generator 10 is shown in which a tunable laser 12 generates a control signal that is applied along with an input signal pulse to be delayed to 50/50 optical coupler 14 in a Sagnac interferometer 16. The Sagnac interferometer 16 includes first and second sections 20 and 22 of wavelength shifting fiber (e.g. HNL-DSF); and a section of dispersive delay inducing fiber 24 (e.g. DCF). In this embodiment, wavelength conversion or shifting (fiber 20), wavelength dependent delay (fiber 24) and wavelength reconversion or un-shifting (fiber 22) are thus folded into a loop or ring configuration. The Sagnac loop configuration is convenient because it gives a method for combining and subsequently filtering the pump and the signal/idler, though its implementation can be challenging because all of the functions are coupled together. A compensation fiber 26 is used to compensate for pulse broadening effects that usually occur when pulses of light propagate in the presence of dispersion. Finally, a circulator 28 is employed to direct the incoming and outgoing signals as indicated.

[0018] Turning now to FIG. 2, another all-optical delay generator 50 is illustrated that is configured in accordance with a second embodiment of the invention. The pulse signal to be shifted and the control or pump signal from a tunable laser 52 are combined in an 80/20 coupler 54 and pass straight through a circulator 56. Next, they pass through a compensation fiber 58, which can be DCF, for example, to handle ahead of time any pulse broadening that will occur in later steps. Next, the pulses pass through a wavelength shifting fiber 60 (e.g. FWM in HNL-DSF) and then through a wavelength dependent delay fiber 62 (e.g. DCF). Next, the pulses reflect off of a mirror 64 and propagate from left to right. They go again

through the wavelength dependent delay fiber 62 and then are wavelength shifted back to the original signal wavelength by the HNL-DSF 60. Pulse broadening is further compensated in the compensation fiber 58 and finally the signal is taken out of the system using the circulator 56 and passed through an optical bandpass filter 66 to remove any residual pump or idler that may be left over.

[0019] There are numerous variations on the designs of FIGs. 1 and 2 which may include Faraday rotator mirrors for retroreflection, tunable fiber Bragg gratings for coarse delay adjustment, soliton pulse propagation to negate temporal pulse broadening and multiple control lasers to achieve polarization-independent operation.

[0020] With reference to FIG. 3, an FOPA based continuously tunable optical delay generator 100 is illustrated that is constructed in accordance with a third preferred embodiment. This embodiment was actually constructed for use in an experiment to verify operation of the present invention as will be discussed later in conjunction with FIGs. 4 and 5. The laboratory use of FOPA technology is becoming commonplace and there are many potentially useful FOPA devices that have been proposed for use in communication systems. Examples include broadband amplifiers, signal regenerators and wavelength converters.

[0021] The optical delay generator 100 of FIG. 3 is actually quite similar in the design to the generator 50 of FIG. 2. The main differences are that the generator 100 requires injection of another control or pump signal for the wavelength reconversion and tunable bandpass filters are added to reduce noise.

[0022] The optical delay generator 100 includes an FOPA 102 that is formed by a tunable CW laser 104, a first 50/50 coupler 105 that splits the control signal from the laser 104 along two paths, first and second amplitude modulators 106, first and second EDFAs 108 (erbium doped fiber amplifiers), first and second TBPFs 110 (tunable bandpass filters), second and third 50/50 couplers 112 and 114, and a 1 km long HNL-DSF 116 for wavelength conversion. It should be noted that the two signal paths (a and b) are needed to suppress another nonlinear optical effect called Brillouin scattering. The presence of Brillouin scattering will significantly reduce the efficiency of wavelength conversion. To provide the desired pulse delay, the FOPA 102 is interfaced through the second 50/50 coupler 114 and another TBPF 118 through a DCF 120 and a mirror 122.

[0023] The graphical illustrations of pulses labeled 1 through 5 in FIG 3 depict the evolution of the pulse delay through the generator 100. In summary, (1) synchronous pump and signal pulses enter the system; (2) wavelength conversion due to four-wave mixing (FWM) results in an idler pulse synchronous with respect to the pump and signal; (3)

propagation through DCF 120 results in a time-shifted idler with respect to the original signal (which has been filtered away, but is shown as a dotted pulse), (4) wavelength conversion results in a new pulse at the original signal wavelength which is synchronous with respect to the idler, and (5) the pump and idler are filtered from the signal pulse.

[0024] With reference now to the operation of the generator 100 in greater detail, signal pulses of 1.2-ps duration are taken from a tunable Ti:Sapphire-pumped, optical-parametric oscillator system (not shown). A small portion of the signal is detected at point “a”, and the detected signal is used to modulate the tunable CW laser 104, which serves as the primary pump laser. The transfer characteristics of the detector and modulators 106 result in pump pulses of roughly 100 ps in duration, thus suppressing Brillouin scattering of the pump within the FOPA 102. The pump pulses are optically amplified and combined synchronously with the signal pulses via the second 50/50 coupler 112. Parametric amplification of the signal pulses within the 1-km-long highly-nonlinear dispersion-shifted fiber (HNL-DSF) 116 results in the generation of idler pulses that are spectrally shifted according to $2\omega_p = \omega_s + \omega_i$ where ω_p , ω_s , and ω_i are the angular frequencies of the pump, signal and idler pulses, respectively. After emerging from the HNL-DSF 116, the pump and signal pulses are filtered from the idler pulses which then propagate forward and back through the span of dispersion compensating fiber (DCF) 120, which in an exemplary embodiment, was selected to have a group velocity dispersion of -74 ps/nm. The temporal delay that the idler pulses acquire is proportional to the original wavelength shift times the group-velocity dispersion coefficient of the DCF. In a manner similar to that used at the input of the system, a secondary pump is modulated by detecting the photocurrent of the idler at point “b.” The idler pulses are now spectrally shifted back to the original signal wavelength using parametric amplification in the reverse direction through the HNL-DSF 116. Finally, after passing through a circulator 124, the pump and idler are filtered from the delayed output signal as it is fed through another TBP 126.

[0025] In the actual experiments conducted on the pulse delay generator of FIG. 3, the following results were obtained. The zero-dispersion wavelength for the HNL-DSF used in the experiments was measured to be 1551 nm (plus or minus 2 nm). FIG. 4A shows a plot of the expected parametric gain in a single pass through the HNL-DSF as a function of pump wavelength for a signal wavelength of 1565 nm. The peak pump power used in this calculation was 300 mW, which is consistent with the experimental conditions. The plot indicates that there is appreciable gain for pump detunings as large as 12 nm, corresponding to signal-to-idler wavelength conversions of 24 nm. Also shown in FIG 4A is the

experimentally measured delay of the signal pulses at the output of the system. Temporal traces of the delayed signal output pulse for different pump wavelengths are shown in FIG 4B. The pulses are still well shaped at the output of the system, and delays in excess of 800 ps have been demonstrated. In principle, by using a DCF with larger GVD, and including the corresponding amount of pulse GVD precompensation compression at the input, delays of thousands of ns can be produced.

[0026] Depicted in FIG 5 are the optical spectra of the input and the delayed pulses. The central wavelength of the output is exactly the same as the input, which is a consequence of generating the pump pulses for both wavelength conversion stages from the same CW laser. The spectral shape is nearly identical down to 8 dB from the peak, at which point we observe considerable noise in the sidebands. This noise is comprised of a combination of amplified spontaneous emission from the erbium-doped fiber and from the parametric amplifiers. The sidebands can be suppressed to some extent by enhanced filtering of the pump at the input to the system as well as by using a narrower spectral filter at the output. It is also worth noting that the sideband noise observed in FIG 5 can be reduced by using parametric amplifiers pumped with two phase-modulated CW pump lasers compared with those pumped by a single pulsed laser.

[0027] The experiments demonstrated a continuously variable, all-optical pulse delay that operates in the 1.5 μm telecommunication window. Variable nanosecond as well as picosecond delays have been obtained, but the approach is flexible enough to be used to generate either narrower or broader spans of delay, depending on the needs of a particular user. Delays to pulse width ratios of more than 100 have been demonstrated.

[0028] Although the invention has been disclosed in terms of a number of preferred embodiment and variations thereon, it will be understood that numerous additional modifications and variations could be made thereto without departing from the scope of the invention as defined in the following claims.

What is Claimed is:

1. A method for imparting a controllable delay to an optical pulse comprising the steps of:
 - applying a selected wavelength shift to said pulse using an all-optical process;
 - propagating said pulse through a delay inducing component that generates a wavelength dependent delay of said pulse; and
 - shifting the wavelength of said pulse back to its original wavelength.

2. The method of claim 1, wherein said all-optical process is selected from the group comprising cross-phase modulation, cross-gain modulation, self-phase modulation, four-wave mixing and parametric mixing.

3. The method of claim 2, wherein a selected wavelength shift is applied to said pulse by combining said pulse with a pump laser pulse, and subjecting said pulses to parametric amplification within a highly-nonlinear dispersion-shifted fiber (HNL-DSF), thereby resulting in the generation of idler pulses that are spectrally shifted according to $2\omega_p = \omega_s + \omega_i$ where ω_p , ω_s , and ω_i are the angular frequencies of the pump, signal, and idler pulses, respectively.

4. The method of claim 3, wherein said step of propagating said pulse comprises propagating said idler pulses forward and back through a span of dispersion compensating fiber (DCF) to impart a delay to the idler pulses that is proportional to the original wavelength shift times the group-velocity dispersion coefficient of the DCF.

5. The method of claim 4, wherein said step of shifting the wavelength of the pulse back comprises spectrally shifting the idler pulse back to the original signal wavelength using parametric amplification in the reverse direction through the HNL-DSF.

6. The method of claim 1, wherein temporal broadening of said pulse is removed by propagating said pulse through a dispersive component having a group velocity dispersion of opposite sign but the same magnitude as the delay inducing component used to generate the delay.

7. The method of claim 1, wherein said steps are carried out by combining said pulse with a pump laser pulse, and passing a said combined pulses first through a section of dispersion shifted fiber to impart a wavelength shift to said pulses; then through a section of dispersive fiber to impart a delay to said pulses that is proportional to the wavelength of the wavelength shifted pulses; and finally through a second section of dispersion shifted fiber to shift the wavelength of said pulse back to the wavelength of the original pulses.

8. A continuously tunable optical delay generator for imparting a variable delay in an optical signal pulse comprising:

an all-optical device for selectively shifting the wavelength of said pulse; and

a dispersive fiber for imparting a wavelength dependent delay to said pulse;

wherein, said all-optical device is configured to shift a wavelength of said pulse from an original value to a shifted value prior to said pulse being passed through said dispersive fiber, and then after said pulse passes through said dispersive fiber, to shift the wavelength of said pulse back to said original value.

9. The optical delay generator of claim 8, wherein said all-optical device employs a process selected from the group comprising cross-phase modulation, cross-gain modulation, self-phase modulation, four-wave mixing and parametric mixing.

10. The optical delay generator of claim 9, wherein said optical device includes a pump laser that generates a pump pulse that is combined with said signal pulse; and a first section highly-nonlinear dispersion-shifted fiber (HNL-DSF) through which said combined pulses are passed, thereby resulting in the generation of idler pulses that are spectrally shifted according to $2\omega_p = \omega_s + \omega_i$ where ω_p , ω_s , and ω_i are the angular frequencies of the pump, signal and idler pulses, respectively.

11. The optical delay generator of claim 10, further comprising a mirror for reflecting pulses that have propagated through said HNL-DSF fiber and said delay inducing dispersion fiber, back through said delay inducing fiber and said HNL-DSF fiber to restore the wavelength of said pulse to said original value.

12. The optical delay generator of claim 10, wherein said HNL-DSF fiber forms part of fiber optic parametric amplifier.

13. The optical delay generator of claim 10, wherein said all-optical device further includes a second section of HNL-DSF fiber for restoring the wavelength of said delayed signal pulse back to said original value, and said first section of HNL-DSF fiber, said dispersive delay inducing fiber and said second section of HNL-DSF fiber are configured in a loop of a Sagnac interferometer.

14. The optical delay generator of claim 8, further including a compensating fiber for removing temporal broadening of said signal pulse that occurs when said pulse passes through said dispersive delay inducing fiber, said compensating fiber having a group velocity dispersion of opposite sign but the same magnitude as the delay inducing component used to generate the delay.

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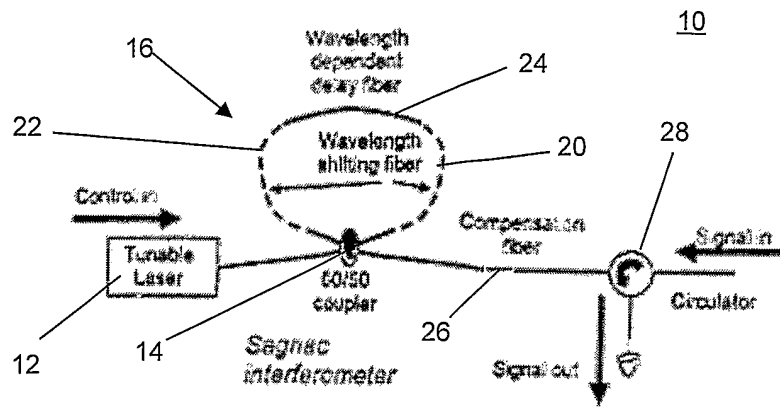


FIG. 1

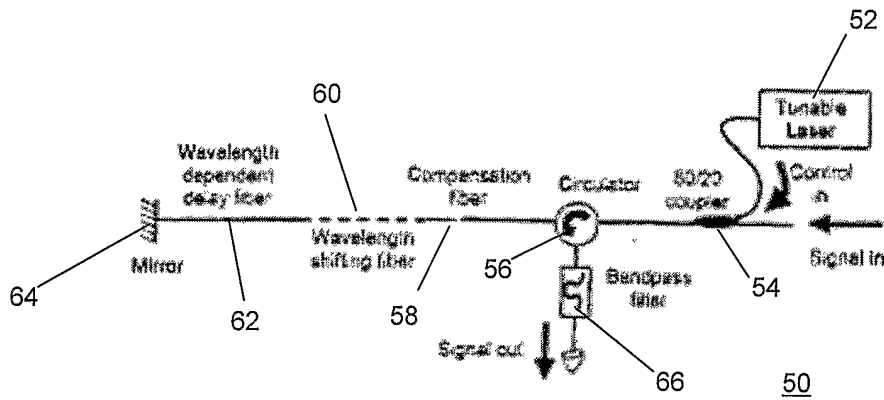


FIG. 2

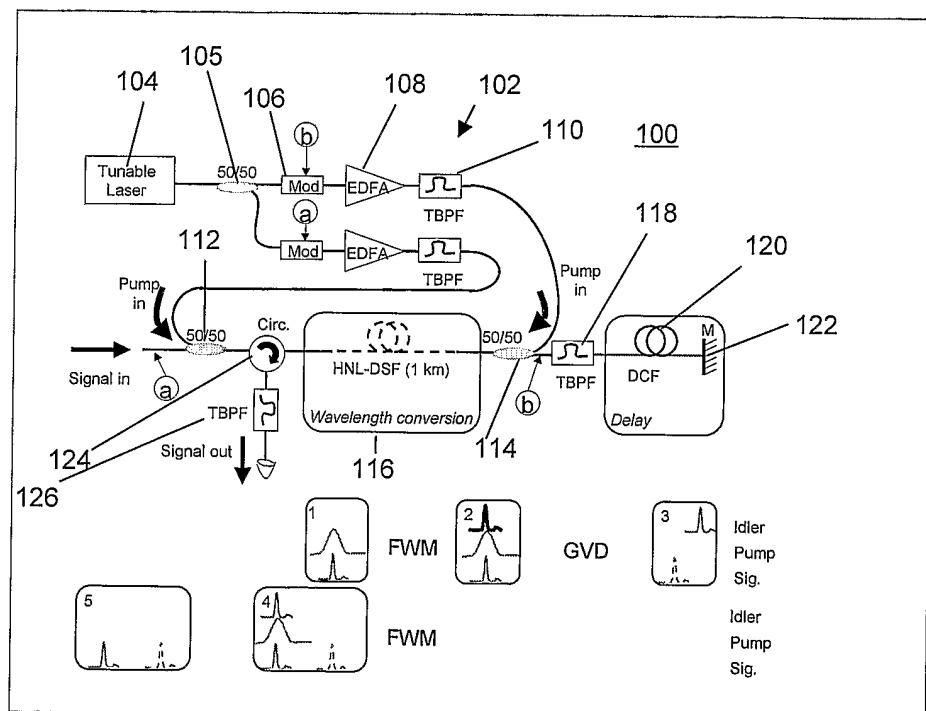
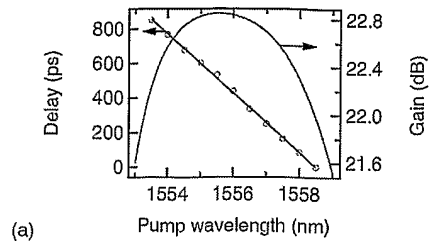


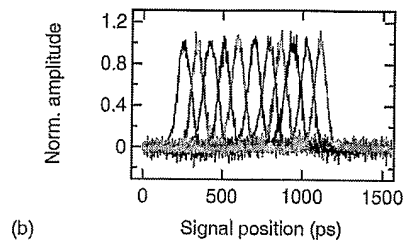
FIG. 3

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(a)

FIG. 4A



(b)

FIG. 4B

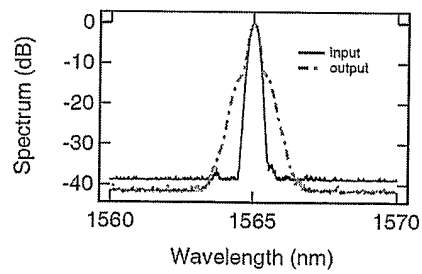


FIG. 5