Title: COMPENSATION OF CHROMATIC DISPERSION USING ETALONS WITH VARIABLE REFLECTIVITY

Abstract: A dispersion compensation system includes one or more etalons (100) cascaded in series to forms a chain. The chain of etalons (100) introduces a cumulative group delay that compensates for chromatic dispersion (450), including possibly dispersion slope (440). At least one of the etalons (100) is tunable, thus allowing the system to be tuned, for example to compensate for different amounts of dispersion and/or manufacturing variations.
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COMPENSATION OF CHROMATIC DISPERSION USING ETALONS WITH VARIABLE REFLECTIVITY

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BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to compensation of chromatic dispersion, including for example compensation of dispersion slope. More specifically, this invention relates to the use of etalons to compensate for chromatic dispersion.

2. Description of the Related Art

As the result of recent advances in technology and an ever-increasing demand for communications bandwidth, there is increasing interest in optical communications systems, especially fiber optic communications systems. This is because optical fiber is a transmission medium that is well-suited to meet the demand for bandwidth. Optical fiber has a bandwidth which is inherently broader than its electrical counterparts. At the same time, advances in technology have increased the performance, increased the reliability and reduced the cost of the components used in fiber optic systems. In addition, there is a growing installed base of laid fiber and infrastructure to support and service the fiber.

However, even fiber optic systems have limits on price and performance. Chromatic dispersion is one basic phenomenon which limits the performance of optical fibers. The speed of a photon traveling along an optical fiber depends on the index of refraction of the fiber. Because the index of refraction is slightly dependent on the frequency of light, photons of different frequencies propagate at different speeds. This effect is commonly known as chromatic dispersion. Chromatic dispersion causes optical signal pulses to broaden in the time domain. In addition, chromatic dispersion is cumulative in nature. Therefore, optical signals which travel longer distances will experience more
chromatic dispersion. This limits the signal transmission distance over which high bit rate signals can be transmitted, even with the use of narrow linewidth lasers and low chirp external modulators. For instance, signals at 10 Gbps can travel roughly 80 km in a standard SMF-28 single mode fiber before adjacent digital bits start to interfere with each other. At 40 Gbps, this distance is reduced to 6 km. Chromatic dispersion is a significant problem in implementing high speed optical networks.

[0004] Several different approaches have been proposed to compensate for the effects of chromatic dispersion and, therefore, extend the signal transmission distance. They include systems based on dispersion compensating fiber, fiber Bragg gratings, photonic integrated circuits and etalons.

[0005] Dispersion compensating fibers (DCF) are optical fibers which have chromatic dispersion which is opposite in sign to the chromatic dispersion in “normal” fibers. Thus, propagation through a length of DCF cancels the chromatic dispersion which results from propagating through standard single mode fiber. At the present time, DCF is one of the leading commercial technologies for the compensation of chromatic dispersion and a significant number of chromatic dispersion compensating devices is based on DCF. However, DCF has several significant disadvantages. First, long lengths of DCF are required to compensate for standard fiber. For example, a typical application might require 1 km of DCF for every 5 km of standard fiber. Thus, 100 km of standard fiber would require 20 km of DCF. These amounts of DCF are both expensive and bulky. Second, DCF solutions are static. A 20 km length of DCF will introduce a specific amount of dispersion compensation. If more or less is required, for example due to changes in the overall network architecture, a different DCF solution must be engineered. The existing 20 km of DCF cannot be easily “tuned” to realize a different amount of dispersion compensation, making it unsuitable for agile telecommunications network applications. Third, DCF is a type of fiber and suffers from many undesirable fiber characteristics, typically including undesirable fiber nonlinearities and high losses. A 20 km length of fiber can introduce significant losses. Fourth, standard single mode fibers have non-uniform dispersion values over a wide bandwidth, resulting in a second-order dispersion effect commonly referred to as dispersion slope. DCF solutions typically do not do a good job in compensating for dispersion slope, leaving behind some uncompensated residual dispersion.
Fiber Bragg gratings (FBG) have emerged over the past few years as a promising candidate for the compensation of chromatic dispersion. A fiber Bragg grating is a length of fiber into which Bragg gratings have been formed. Various groups have proposed different architectures for using FBGs to compensate for chromatic dispersion. For example, see Fig. 1 in C.K. Madsen and G. Lenz, “Optical all-pass filters for phase response design with applications for dispersion compensation,” IEEE Photonics Technology Letters, vol. 10, no. 7, July 1998, pp. 994-996. However, practical implementation of FBG solutions remains difficult. Engineering limitations have resulted in less than acceptable dispersion compensation. Finding reproducible and reliable processes to make a dispersion compensator based on FBGs remains very challenging. In addition, Bragg gratings are inherently narrow band devices so FBG-based dispersion compensators typically have a narrow operating bandwidth. It is also difficult to tune FBGs to achieve different amounts of dispersion compensation.

Architectures based on planar waveguides have also been proposed. For example, the paper referenced above suggests an approach for compensating for chromatic dispersion using an all-pass filter approach based on ring structures in planar waveguides. However, this approach is inherently expensive and polarization sensitive.

Finally, around 1990, it was disclosed that the phase response of a single etalon has a nonlinear relationship with frequency. See L.J. Cimini Jr., L.J. Greenstein and A.A.M. Saleh, “Optical equalization to combat the effects of laser chirp and fiber dispersion,” J. Lightwave Technology, vol. 8, no. 5, May 1990, pp. 649-659. Furthermore, it was proposed that an etalon could be used to compensate for chromatic dispersion. Since that time, various etalon-based architectures have been suggested. However, most, if not all, of these architectures suffer from significant drawbacks. Many of them simply cannot attain the necessary performance. They often suffer from too much group delay ripple (e.g., >20 ps) and/or too narrow an operating bandwidth. In addition, most, if not all, designs are static. The designs cannot be easily tuned to achieve different amounts of dispersion compensation. In addition, they typically do not adequately compensate for dispersion slope.

Thus, there is a need for dispersion compensation systems which can be tuned to achieve different amounts of dispersion compensation, including different amounts of
dispersion slope compensation for some applications. It is also desirable for these systems to operate over a large bandwidth and to be capable of achieving low group delay ripple.

SUMMARY OF THE INVENTION

[0010] The present invention overcomes the limitations of the prior art by providing a dispersion compensation system in which one or more etalons are cascaded in series to form a chain. The chain of etalons introduces a cumulative group delay that compensates for chromatic dispersion. At least one of the etalons is tunable, thus allowing the system to be tuned, for example to compensate for different amounts of dispersion, dispersion slope and/or manufacturing variations.

[0011] In one implementation, the dispersion compensation system includes a chain of at least one etalon stage. Each etalon stage includes an input port, an output port, an optical path from the input port to the output port; and an etalon located in the optical path. The etalon has a front dielectric reflective coating and a back dielectric reflective coating. In at least one etalon stage, the front reflective coating of the etalon has a reflectivity that varies according to location on the front face. The chromatic dispersion of the etalon is tunable according to a point of incidence of the optical path on the front reflective coating. The free spectral range may also be tunable. The cumulative chromatic dispersion of the chain of etalon stages substantially compensates for chromatic dispersion over an operating bandwidth.

[0012] In one application, the system corrects for chromatic dispersion over an operating bandwidth within each of a plurality of wavelength channels. The chromatic dispersion may vary from channel to channel. For example, the variation may be characterized by a dispersion slope which is substantially compensated for by the chain of etalon stages. In one implementation, the chain of etalon stages can be tuned to compensate for a range of dispersion slopes. In one variation, over the range of dispersion slopes, the chromatic dispersion of the chain of etalon stages is approximately constant at a reference wavelength. This system can be used to adjust dispersion slope while maintaining a constant dispersion offset at the reference wavelength. In another implementation, the chromatic dispersion of the chain of etalon stages is a substantially constant function of...
wavelength but can be tuned to compensate for a range of dispersion offsets. The two systems together can be used to tune both dispersion slope and dispersion offset.

[0013] In one embodiment, the channel spacing is consistent with the ITU grid as defined in ITU G.692 Annex A of COM 15-R 67-E. In some embodiments, the plurality of wavelength channels includes wavelength channels from one of the following communications bands: the C-band (1528-1565 nm), the L-band (1565-1610 nm) and the S-band (1420-1510 nm).

[0014] In one implementation, the front coating has a reflectivity which varies according to a first coordinate \( x \). The free spectral range varies according to a second orthogonal coordinate \( y \). For example, the tunable free spectral range may be implemented by including a gradient index material as part of the body of the etalon, where the refractive index varies as a function of the coordinate \( y \). Moving the point of incidence in the \( y \) direction tunes the free spectral range. In one implementation, a temperature controller coupled to the etalon controls temperature of the etalon and the phase of the optical path in the etalon can be tuned by varying the temperature.

[0015] Other aspects of the invention include etalons and etalon stages suitable for use in the systems described above, and methods related to the foregoing.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0016] The invention has other advantages and features which will be more readily apparent from the following detailed description of the invention and the appended claims, when taken in conjunction with the accompanying drawings, in which:

[0017] FIG. 1 is a block diagram of a dispersion compensation system according to the invention.

[0018] FIG. 2 is a perspective view of a tunable etalon.

[0019] FIG. 3A is a graph of group delay as a function of wavelength for different values of reflectivity.
[0020] FIG. 3B is a graph of group delay as a function of wavelength illustrating the quasi-periodic nature of the group delay function.

[0021] FIGS. 4A-4B are graphs of reflectivity as a function of wavelength for different example coatings.

[0022] FIG. 5A is a graph of group delay as a function of wavelength for a three-etalon dispersion compensation system.

[0023] FIG. 5B is a table listing parameters for realizing different values of chromatic dispersion.

[0024] FIG. 5C is a graph of dispersion tuning range in a channel pass band as a function of wavelength.

[0025] FIGS. 6A-6B are graphs illustrating the reflectivity and phase of etalon front coatings.

[0026] FIGS. 7A-7D are graphs of reflectivity and phase shift as a function of wavelength for an example dispersion compensation system.

[0027] FIGS. 8A-8D are graphs illustrating dispersion compensation of the example system of FIG. 7.

[0028] FIGS. 9A-9B are side views of variable reflectivity etalons having a top layer with continuously variable thickness.

[0029] FIGS. 9C-9D are side views of tunable etalons having a gradient index material and a top layer with continuously variable thickness.

[0030] FIG. 10 is a side view of a tunable etalon having a top layer with stepwise variable thickness.

[0031] FIGS. 11A-11C are side views of a tunable etalon illustrating one method for manufacturing the etalon.
[0032] FIG. 12 is a top view of an etalon stage in which an optical beam is translated relative to a stationary tunable etalon.

[0033] FIG. 13 is a top view of an etalon stage in which a tunable etalon is translated relative to a stationary optical beam.

[0034] FIGS. 14A-14B are a perspective view and top view of an etalon stage that utilizes a rotatable beam displacer.

[0035] FIGS. 15A-15B are top views of an etalon stage that utilizes a moveable reflective beam displacer.

[0036] FIG. 16 is a top view of an etalon stage that utilizes a MEMS beam displacer.

[0037] FIG. 17 is a top view of an etalon stage that utilizes a free space circulator and a dual fiber collimator.

[0038] FIG. 18 is a top view of an etalon stage that utilizes separate input and output fibers.

[0039] FIGS. 19A-19B are functional block diagrams of etalon stages with separate input and output fibers.

[0040] FIGS. 20A-20C are side views of etalon stage using refractive wedges, mirrors, and total internal reflection with multiple bending, respectively.

[0041] FIG. 20D is a side view of an etalon stage with an asymmetric optical path.

[0042] FIG. 21 is a side view of an etalon stage with beam folding mirrors.

[0043] FIG. 22A is a graph of reflectivity as a function of layer thickness.

[0044] FIG. 22B is a graph of phase shift and wavelength shift in spectral response as a function of layer thickness.
DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0045] FIG. 1 is a block diagram of a dispersion compensation system 10 according to the invention. The system includes at least one etalon stage 20A-20M, preferably two or more. Each etalon stage 20 includes an input port 22, an output port 24 and an etalon 30. Within the etalon stage 20, light travels along an optical path 26 from the input port 22, through the etalon 30 to the output port 24.

[0046] The etalon stages 20 are cascaded to form a chain. In particular, the output port 24A of etalon stage 20A is coupled to the input port 22B of the next etalon stage 20B in the chain, and so on to the last etalon stage 20M. The input port 22A of the first etalon stage 20A serves as the input of the overall system 10 and the output port 24M of the last etalon stage 20M serves as the output of the overall system 10.

[0047] In the example of FIG. 1, the input ports 22 and output ports 24 are collocated. More specifically, incoming light arrives via fiber 31 and outgoing light exits via the same fiber 31, but propagating in the opposite direction. A circulator 36 is used to separate the incoming and outgoing beams. Thus, light propagates through the overall system 10 as follows. Light enters the system 10 at input 52 and is directed by circulator 36A via fiber 31A to etalon stage 20A. Within the etalon stage 20A, the light is incident upon etalon 30A at point 35A. Upon exiting etalon stage 20A, the light reenters fiber 31A to circulator 36A. Circulator 36A directs the light to fiber 33A and the next etalon stage 20B. The light propagates through the etalon stages 20 until it finally exits at output 54.

[0048] The etalon stages 20 can be coupled by devices other than a circulator 36. In cases where the input port 22 and output port 24 are collocated, different devices can be used to separate the incoming and outgoing beams. This general class of device shall be referred to as 3 dB couplers since they typically introduce an inherent 6 dB loss (3 dB on each pass through the device). Some examples of 3 dB couplers include waveguide couplers and fiber couplers. Circulators are an increasingly attractive alternative to 3 dB couplers since they typically introduce about 1.4 dB loss. In another embodiment, the input port 22 and output port 24 are physically separated. For example, the incoming beam may arrive on one fiber and the outgoing beam on a different fiber. See FIGS. 17-21 below for an example of this approach. In the examples of FIGS. 17-21, a dual fiber collimator is used
to connect one etalon stage to the next and can have significantly less loss than a 3 dB coupler.

[0049] Each etalon 30 has a front dielectric reflective coating 32 and a back dielectric reflective coating 34. In at least one of the etalon stages 20, a point of incidence 35 of the optical path 26 on the front reflective coating 32 is tunable, meaning that the point of incidence 35 can be moved to different locations on the front reflective coating 32. The front reflective coating 32 of this particular etalon 30 has a reflectivity that varies according to location. At each location, the reflectivity may also vary by wavelength. Thus, the effective wavelength-dependent reflectivity of the etalon 30 can be adjusted by adjusting the point of incidence 35. In addition, the free spectral range of the etalon 30 may also be tunable.

[0050] FIG. 2 is a perspective view of such a tunable etalon 100. The etalon 100 includes a transparent body 110 having a front surface 112 and a back surface 114. The front surface 112 and back surface 114 are substantially plane-parallel.

[0051] In one implementation, the transparent body 110 is made from a single block of material, as is suggested by FIG. 2. In another implementation, the transparent body 110 is made from blocks of different materials. For example, different materials may be bonded together to form a sandwich-type structure for the transparent body 110 (e.g., see FIGS. 9C-9D). Alternately, some or all of the transparent body 110 may be formed by an air space or liquid crystals. In one implementation, in order from front surface 112 to back surface 114, the transparent body 110 consists of a first block of material, an air space, and a second block of material. The air space is maintained by spacers between the two blocks of material.

[0052] The front and back surfaces 112 and 114 are substantially plane-parallel in the sense that an optical beam 150 which is normally incident upon the front surface 112 also strikes the back surface 114 at an approximately normal angle of incidence. As will be seen in the examples below, it is not essential that the two surfaces 112 and 114 be exactly plane or exactly parallel. In typical cases, a parallelism of better than 0.5 arcsecond is sufficient although actual tolerances will vary by application. Furthermore, in certain cases, the optical path of a beam 150 through the etalon 100 may not be a straight line. For example,
the optical beam 150 may be refracted through an angle at an internal interface in the etalon 100, or the optical path may be folded to form a more compact device by using mirrors, prisms or similar devices. In these cases, the front and back surfaces 112 and 114 may not be physically plane-parallel but they will still be optically plane-parallel. That is, the surfaces 112 and 114 would be physically plane-parallel if the optical path were unfolded into a straight line.

[0053] A back dielectric reflective coating 130 (labeled as back reflective coating 34 in FIG. 1) is disposed upon the back surface 114. The coating 130 has a reflectivity which is substantially 100%. A reflectivity somewhere in the range of 90-100% is typical, although the actual reflectivity will vary by application. If the reflectivity of back coating 130 is less than 100%, then light which is transmitted by the back coating 130 can be used to monitor the etalon 100. In applications where higher loss can be tolerated or the optical beam exits at least partially through the back surface 114, the reflectivity of back coating 130 can be significantly less than 100%. A front dielectric reflective coating 120 (labeled as coating 32 in FIG. 1) is disposed upon the front surface 112. The front reflective coating 120 has a reflectivity that varies according to location on the front surface 112.

[0054] With respect to reflectivity, the etalon 100 functions as follows. An optical beam 150 is incident upon the front surface 112 of the etalon 100 at a normal angle of incidence. The reflectivity of the etalon surfaces 112 and 114 results in multiple beams which interfere, thus producing etalon behavior. If the incoming optical beam is perfectly normal to the etalon’s front surface 112 and the two surfaces 112 and 114 (and the coatings 120 and 130) are perfectly plane parallel, the output beam will exit the etalon 100 at the same location as the original point of incidence and will be collinear with the incoming beam 150 (but propagating in the opposite direction). The incoming and outgoing beams may be spatially separated at front surface 112 by introducing a slight tilt to the beam 150.

[0055] FIG. 2 shows two different positions for optical beam 150. In position A, the optical beam 150A strikes the front surface 112 at point of incidence 155A. In position B, the point of incidence is 155B. As will be shown below, different approaches can be used to tune the point of incidence to different locations on the etalon’s front surface 112 while maintaining normal incidence of the optical beam. Typically, in a packaged stage, the optical beam 150 arrives via an input port, propagates into the etalon 100 and exits via an
output port. In one class of approaches, the input port and/or the etalon 100 are moved in order to tune the point of incidence 155 to different locations. In another class of approaches, the input port and etalon 100 are fixed relative to each other, but a separate beam displacer tunes the point of incidence 155 of the optical beam on the etalon 100.

[0056] At the two different points of incidence 155A and 155B, the front reflective coating 120 has a different reflectivity and/or the reflectivity has a different wavelength dependence. Therefore, optical beam 150A is affected differently by etalon 100 than optical beam 150B. Different wavelengths within each beam 150 may also be affected differently. In effect, the reflectivity of the etalon (including its wavelength dependence) can be adjusted by varying the point of incidence 155.

[0057] The free spectral range of etalon 100 may also be adjusted. A number of different approaches can be used to implement this effect. The free spectral range depends on the optical path length of a round trip through the etalon. Thus, changing the optical path length changes the free spectral range.

[0058] In one class of approaches, the optical path length is changed while the point of incidence is held constant. For example, the optical path length of the etalon for optical beam 150B could be adjusted while the beam remained at point 155B. This can be achieved by varying the physical length of the etalon 100, for example by varying the length of an air space located in the body 110 of the etalon or by changing the spacing between the two reflective coatings 120 and 130. Alternately, the optical path length can be adjusted by varying the index of refraction within the etalon 100.

[0059] In another class of approaches, the free spectral range varies according to location and is tuned by tuning the point of incidence of the optical beam. For example, in the two examples of FIGS. 9C-9D, the body 110 includes a gradient index material 111 bonded to a constant index material 113. In the 1.55 μm example described below, Gradium™, (available from LightPath Technology) or liquid crystal is suitable as the gradient index material 111 and fused silica, BK7 or similar glass can be used as the constant index material 113. The refractive index of the gradient index material 111 varies in the y direction (i.e., perpendicular to the plane of the paper). Thus, the free spectral range of the etalon 100 can be tuned by moving the point of incidence in the y direction.
[0060] The dispersion $D$ introduced by an etalon 100 can be calculated using conventional principles. In particular, the phase modulation $\phi$ introduced by etalon 100 is given by

$$\phi = 2 \tan^{-1} \left( \frac{r \sin \omega T}{1 + r \cos \omega T} \right)$$  \hspace{1cm} (1)

where $r^2 = R$ is the reflectivity of the front coating 120 at the wavelength of interest, the back coating 130 is assumed to be 100% reflective, $T$ is the round-trip delay induced by the etalon, and $\omega$ is the frequency of the optical beam 150. Specifically, $T = OPL/c$ where $c$ is the speed of light in vacuum and $OPL$ is the total optical path length for one round trip through the etalon 100. If the one-way optical path through the etalon is a straight line of length $L$ through material of refractive index $n$, then $OPL = 2nL$. The group delay resulting from Eqn. (1) is

$$\tau(\omega) = - \frac{d\phi(\omega)}{d\omega} = -2rT \frac{r + \cos \omega T}{1 + r^2 + 2r \cos \omega T}$$  \hspace{1cm} (2)

[0061] The dispersion $D$ of the etalon is then

$$D(\lambda) = \frac{d\tau(\lambda)}{d\lambda}$$  \hspace{1cm} (3)

[0062] FIG. 3A is a graph of the group delay $\tau(\lambda)$ as a function of wavelength $\lambda$ for three different values of the reflectivity $R = r^2$ where $\omega = 2\pi c/\lambda$ where $\lambda$ is the wavelength of the optical beam 150. The curves 210, 220 and 230 correspond to reflectivity values $R$ of 1%, 9% and 36%. For simplicity, the optical path length $OPL$ is assumed to be constant for these curves and the reflectivity is assumed to be constant with wavelength. The different values of $R$ are realized by varying the point of incidence 155 of the optical beam 150. For example, the point of incidence 155A in FIG. 2 might have a reflectivity $R$ of 1%, resulting in dispersion $D$ corresponding to the group delay curve 210. Similarly, point 155B might correspond to curve 220 and some other point of incidence might correspond to curve 230. Therefore, the group delay and the dispersion experienced by the optical beam 150 as it propagates through etalon 100 can be varied by varying the point of incidence 155. Note
that in this application, the front and back reflective coatings 120 and 130 cannot be metallic since metallic coatings result in unpredictable phase modulation and the dispersion $D$ depends on the phase modulation $\phi$.

[0063] Furthermore, if the reflectivity were independent of wavelength, the group delay $\tau(\lambda)$ and dispersion $D$ would be periodic functions of the wavelength $\lambda$. The base period of these functions (i.e., the free spectral range of the etalon) is set by the optical path length $OPL$. When the reflectivity varies slowly with wavelength, the group delay $\tau(\lambda)$ is not exactly periodic but is still close to periodic (i.e., quasi-periodic). FIG. 3B is a graph of the quasi-periodic group delay over a broader range of wavelengths (as compared to the graphs in FIG. 3A) for an etalon with wavelength-dependent reflectivity. The spacing of the maximums in the group delay function is almost exactly equal to the free spectral range of the etalon. There may be a very slight variation due to the wavelength dependence. The magnitude of the maximum varies from one “period” to the next as a result of the wavelength dependent reflectivity. The location and spacing of the maxima (or minima) can be adjusted by changing the $OPL$. The location of the maxima and minima are sensitive to changes in the phase of the $OPL$. That is, phase changes in the $OPL$ shifts the curves 220, 230 to the right or left without significantly affecting the base period of the curve.

[0064] The design and selection of materials for etalon 100 depends on the wavelength(s) $\lambda$ of the optical beam 150, as well as considerations such as the end application, manufacturability, reliability and cost. Current fiber optic communications systems typically use wavelengths in either the 1.3 $\mu$m or 1.55 $\mu$m ranges and etalons intended for these systems would use corresponding materials. Obviously, the term “transparent body 110” means transparent at the wavelength of interest.

[0065] In one example, the etalon 100 is designed for use in the 1.55 $\mu$m wavelength range. The incoming optical beam 150 has a center wavelength (or multiple center wavelengths if the optical beam is wavelength division multiplexed) which is consistent with the ITU grid, as defined in the ITU standards.

[0066] The optical path length of body 110 is selected so that the free spectral range of the etalon 100 is matched to the basic periodicity of the ITU grid. For example, the ITU grid defines wave bands which are spaced at 100 GHz intervals. In one application, a fiber
optic system implements one data channel per wave band (i.e., at a channel spacing of 100 GHz) and the free spectral range of the etalon 100 is also approximately 100 GHz, thus matching the ITU grid and the spacing of the wavelength channels. In another application, two data channels are implemented in each wave band. The spacing between channels is then 50 GHz, or half the band to band spacing on the ITU grid. The etalon 100 is designed to have a free spectral range of approximately 50 GHz, thus matching the channel spacing of the wavelength channels. The etalon can be designed to have a free spectral range that matches other periodicities, including those based on standards other than the ITU standards or those which are intentionally different than the ITU standards. For example, the etalon 100 may be intended for an application consistent with the ITU grid but the free spectral range of the etalon 100 may be different than the ITU periodicity in order to introduce variation in the etalon response from one band to the next.

[0067] The front and back surfaces 112 and 114 are plane-parallel to within 0.5 arc seconds and the back reflective coating 130 is a Bragg reflector with enough layers to achieve a reflectivity of over 99%, typically for this particular example. The front reflective coating 120 is a stack containing one or more layers of materials, as shown in the designs of FIGS. 9. The detailed structure of the layers determines the range of reflectivities achievable by the front reflective coating 120 and the wavelength dependence of the reflectivity, both of which depend on the application. The thickness varies in the x direction, so the reflectivity can be tuned by moving the point of incidence in the x direction.

[0068] In one embodiment, the front reflective coating 120 has a relatively flat response over the wavelength. Many coating structure are suitable for this coating design. For example, the front coating can be a stack of three layers, following the design of FIG. 9D (although the specific example in FIG. 9D shows four layers). Working away from the etalon body, the first two layers are quarter wave layers of Y₂O₃ and SiO₂, respectively, having refractive indices of 1.75 and 1.44. The top layer is Ta₂O₅ with a refractive index of 2.07. The thickness of the top layer varies from zero to a quarter wave. The resulting reflectivity of the front reflective coating varies over a range from 0%-40%. The wavelength dependence of this coating is shown in FIG. 4A. Curve 410A shows the reflectivity when the top layer thickness is a quarter wave thick. Curve 410E shows the reflectivity when the top layer thickness is zero. From curve 410E to curve 410A, the
thickness of the top layer increases in uniform steps. Note that the reflectivity does not vary much with wavelength.

[0069] Other coating designs can also give a relatively flat response over the wavelength. Typically, by varying the thickness of top layer 310, a reflectivity variation of 40%-50% can be achieved. This variation can be translated to different offsets (e.g., to a range of 10%-60%, or 20%-70%, etc. for a variation of 50%) by varying the number and materials of the layers 320 under the top layer 310. Typically, in the design of FIG. 9, only the top layer 310 varies in thickness. The underlying layers 320 typically are not exposed. Many materials are suitable for front reflective coating 120, such as Ta₂O₅, TiO₂, SiO₂, SiO, Pr₂O₃, Y₂O₃, Al₂O₃, HFO₂ and AlF₃.

[0070] In another embodiment, the reflectivity of the front reflective coating 120 varies significantly with wavelength. Many coating designs can achieve a desired wavelength dependency by using non-quarter wave thicknesses. In one example, the front coating includes five layers of material. Working away from the etalon body, the layers are (1.779 TiO₂, 1.514 Al₂O₃, 1.115 TiO₂, 0.131 SiO₂, and 0.221 HFO₂). The number in front of the material name is the optical path length of that layer, which is the product of refractive index and thickness of each layer. The optical path length is measured in units of a reference wavelength. The top layer is HFO₂. Its thickness varies at different locations. FIG. 4B shows the reflectivity of this coating as a function of wavelength. Different curves in FIG. 4B correspond to different thicknesses of the top layer. From curve 420E to curve 420A, the top layer thickness changes from 0 to 0.113 μm. One characteristic of this coating is that the slope of the reflectivity curves 420 change with varying thickness for the top layer, but the reflectivity at the center wavelength remains relatively constant. This characteristic will be used to achieve tunable slope compensation.

[0071] Referring to FIG. 1, each etalon stage 20 introduces a certain group delay τ(ω) and corresponding dispersion D(λ). These quantities are additive. The cumulative group delay produced by all of the stages 20 is the sum of the group delays produced by each etalon stage 20. Similarly, the cumulative dispersion produced by all of the stages 20 is the sum of the dispersions produced by each etalon stage 20. By appropriately selecting the group delay introduced by each stage 20, a substantially linear group delay curve (or a
substantially constant dispersion) can be achieved for the overall system over a certain operating bandwidth.

Furthermore, if the free spectral ranges of all the etalon stages are approximately equal, then the group delay curve will also be approximately periodic. Thus, the overall system can be used to substantially compensate for chromatic dispersion over an operating bandwidth within each of a multiplicity of wavelength channels. For example, the wavelength channels may be spaced by 100 GHz and the overall system may substantially compensate for chromatic dispersion over an operating bandwidth of 60 GHz within each wavelength channel for a certain number of channels. For some applications, it is preferable that the overall system be able to compensate for chromatic dispersion over all wavelength channels within a communications band, for example the C-band (1528-1565 nm), the L-band (1565-1610 nm) or the S-band (1420-1510 nm).

In many fibers, the chromatic dispersion also varies from channel to channel. For example, the chromatic dispersion may be characterized by a dispersion slope. As will be shown below, by correct selection of the reflectivities and free spectral ranges, enough aperiodicity can be introduced into the overall system to compensate for the dispersion slope (or other channel to channel variations in the chromatic dispersion).

More specifically, suppose that there are a total of \( m \) etalon stages, as shown in FIG. 1. Let \( \omega = 2\pi c/\lambda = 2\pi f \), where \( \lambda \) is the wavelength in vacuum and \( f \) is the frequency. Each individual stage \( i \) is characterized by a reflective coefficient \( r_i \) and round-trip delay \( T_i = 2(n_i L_i + \delta_i)/c \), where \( n_i \) and \( L_i \) are the refractive index and nominal physical length of the body of the etalon (actually, the summation of product \( nL \) for all materials in the body) and \( \delta_i \) is a variable phase tuning factor. Eqn. (2) can be expressed for the \( i \)-th stage as

\[
\tau_i(\lambda) = \left( \frac{4r_i(n_i L_i + \delta_i)}{c} \right) \left( \frac{4\pi(n_i L_i + \delta_i)}{\lambda} \right) \frac{r_i + \cos\left( \frac{4\pi(n_i L_i + \delta_i)}{\lambda} \right)}{1 + r_i^2 + 2r_i \cos\left( \frac{4\pi(n_i L_i + \delta_i)}{\lambda} \right)}, \quad i = 1, 2, \ldots, m
\]

As shown in Eqn. (4), the group delay \( \tau \) is affected by both the reflective coefficient \( r_i \) and the optical path length \( (n_i L_i + \delta_i) \). It is possible to obtain a quasi-linear
group delay by superimposing multiple group delay curves with proper phase matching conditions. To illustrate the concept of employing multiple stages to achieve a tunable quasi-linear group delay, the following example uses a three-stage configuration following the architecture in FIG. 1 (with $M=m=3$). The same idea can be extended to more or fewer stages in a straightforward manner. Increasing the number of stages reduces group delay ripple but at a cost of higher insertion loss and higher material cost. With enough stages, operating bandwidths which exceed 50% of the free spectral range of the etalons are possible.

[0076] The total group delay $\tau_T(\lambda)$ for an $m$-stage configuration can be expressed as

$$\tau_T(\lambda) = \sum_{i=1}^{m} \tau_i(\lambda)$$

(5)

Hence, the dispersion $D$ of the multi-stage system is related to the total group delay $\tau_T(\lambda)$ by

$$D(\lambda) = \frac{d\tau_T(\lambda)}{d\lambda}$$

(6)

[0077] Generally, better performance can be achieved by adding more degrees of freedom. Better performance typically means larger dispersion tuning range, less residual dispersion and/or ripple (i.e., better dispersion compensation) and/or a wider operating bandwidth. More degrees of freedom typically means more stages 20, more variability in the reflectivity $R$ and/or more variability in the optical path length $OPL$ (which is typically implemented as more variability in the free spectral range and/or more variability in the tuning factor $\delta$). Furthermore, with enough variability, a system 10 can be tuned to compensate for different amounts of chromatic dispersion within a wavelength channel and/or different amounts and types of channel to channel variation in the chromatic dispersion.

[0078] The tunability can also compensate for manufacturing variability. For example, consider a situation in which the target reflectivity for a stage is $15\% \pm 0.01\%$. One approach would be to manufacture a constant-reflectivity etalon with a reflectivity of between 14.99 and 15.01%. An alternate approach would be to manufacture a variable
reflectivity etalon which is tunable to 15% reflectivity. For example, if the etalon nominally could be tuned over a range of 1%-40%, then even a manufacturing tolerance of ±1% (as opposed to ±0.01%) would result in an etalon which could reach the required 15% reflectivity.

[0079] FIG. 5A is a graph of group delay as a function of wavelength for the three-etalon dispersion compensation system. The target group delay for the system is curve 510 over the operating bandwidth 520. Curves 530A, 530B and 530C show the group delay for each of the three stages and curve 540 is the total group delay for the system. Curve 550 shows the residual ripple. Note that each stage is tuned to a different reflectivity $R$ (as evidenced by the different values for the peaks of the individual group delays 530) and to a different optical path length $OPL$ (as evidenced by the different wavelengths at which the individual peaks occur). In fact, by tuning the stages to different values of reflectivity $R$ and optical path length $OPL$, not only can the system compensate for a specific amount of chromatic dispersion, it can also be tuned to compensate for different amounts of chromatic dispersion.

[0080] In addition, since the group delays and dispersions are periodic, the system can compensate for chromatic dispersion on a per-channel or multi-channel basis. In other words, if the dispersion compensation system is used in an application with a predefined and periodic spacing of wavelength bands (e.g., the 50 GHz or 100 GHz spacing of the ITU grid), then the etalons can be designed to have a free spectral range that is approximately equal to the periodic spacing. In this way, the dispersion compensation system can be used over multiple wavelength bands. For example, the system may be designed to cover all of the wavelength bands in one of the commonly used communications bands: the C-band (1528-1565 nm), the L-band (1565-1610 nm) or the S-band (1520-1510 nm).

[0081] FIG. 5B is a table listing specific parameters for realizing different values of chromatic dispersion. The column $D$ is the target dispersion. The six columns $r_i$ and $\delta_i$ are the values of reflective coefficient $r$ (recall, reflectivity $R$=$r^2$) and OPL tuning factor $\delta$ for each of the three stages $i$. Group Delay Ripple is the peak to peak deviation between the target group delay and the actual group delay realized. The curves in FIG. 5A correspond to the row for $D = -250$ ps/nm.
[0082] FIG. 5C illustrates the flexibility of this system as it is tuned to dispersion values ranging from -500 to +500 ps/nm. Each curve is generated by tuning the reflectivities and OPL tuning factors to different values. In other words, all of the curves shown in FIG. 5C are generated by a single physical system that is tuned to compensate for different values of dispersion. Note that the system can achieve zero dispersion with low ripple. The curves shown in FIG. 5C are merely examples. The system can be tuned to achieve dispersion values other than those shown, including dispersions with magnitude greater than 500 ps/nm.

[0083] In order to realize a specific dispersion, the system is tuned to specific values of reflective coefficient $r$ and OPL tuning factor $\delta$. These target values can be determined for each value of dispersion using standard optimization techniques. To a first order, the optimization problem can be described as, for a given operating bandwidth and a given target dispersion $D$, find the set of parameters $(r, \delta)$ which minimizes some error metric between the actual dispersion realized and the target dispersion or, equivalently, between the actual group delay realized and the target group delay. For constant dispersion, the target group delay will be a linear function of wavelength. Examples of error metrics include the peak-to-peak deviation, maximum deviation, mean squared deviation, and root mean squared deviation. Examples of optimization techniques include the multidimensional downhill simplex method and exhaustive search. Exhaustive search is feasible since the degrees of freedom $(r, \delta)$ typically have a limited range.

[0084] There can be multiple solutions for a given value of dispersion and factors in addition to the error metric typically are used to select a solution. For example, one such factor is the sensitivity of the solution to fluctuations in the parameters. Less sensitive solutions are usually preferred. Another factor is the manufacturability or practicality of the solution.

[0085] The solutions $(r, \delta)$ for different dispersion values and/or operating bandwidths typically are calculated in advance. They can then be stored and recalled when required. In one embodiment, system 10 includes a lookup table that tabulates the parameters $(r, \delta)$ as a function of dispersion and/or bandwidth. When a specific dispersion
compensation is required, the corresponding parameters \((r, \delta)\) are retrieved from the lookup table and the stages are tuned accordingly.

[0086] In order to tune the stages, a conversion from the parameters \((r, \delta)\) to some other parameter is typically required. In the example three-stage system described above, the reflective coefficient is converted to a corresponding physical position and OPL tuning factor is converted to a corresponding temperature. There are many ways to achieve this. In one approach, each stage is calibrated and the calibration is then used to convert between \((r, \delta)\) and \((\kappa, T)\).

[0087] FIG. 5 shows dispersion compensation for either a single wavelength channel or for a number of wavelength channels where the dispersion at each channel is assumed to be the same. Most fiber has different dispersion at different channels. The dispersion of the optical fiber can be approximated by a linear function

\[
D(\lambda) = D_0 + \alpha(\lambda - \lambda_0) \tag{7}
\]

where \(\lambda_0\) is the reference wavelength, \(D_0\) is the dispersion at the reference wavelength, and \(\alpha\) is the dispersion slope.

[0088] In one implementation, FSR mismatch is used to compensate for this dispersion slope. In other words, the FSR of the etalon is chosen to be slightly different from the channel spacing of the ITU grid. For example, if the channel spacing is 50GHz, the FSR of the etalon might be chosen to be somewhere from 49.97GHz - 50.03GHz, in order to compensate for dispersion slope values. Although etalons with FSR mismatch can compensate for different dispersions at different channels, the performance typically cannot be optimized for all channels simultaneously. Some channels may still suffer large group delay ripple that degrades the optical signal quality.

[0089] Referring to Eqn. 4, the group delay of system 10 is determined by the reflectivity and phase shift of each etalon. In order to improve the overall system performance, the reflectivity and phase shift of each individual etalon can be selected so as to improve the performance at each channel of interest. For example, if the system is to be used in the C-band, the performance can be optimized at each relevant wavelength in the C-band. FIGS. 6A-6B show these etalon parameters for a system which compensates for
chromatic dispersion introduced by 100 km of E-LEAF fiber. FIG. 6A shows the reflectivity of the front coating. FIG. 6B shows the phase shift of each etalon. Both of these parameters are a function of wavelength. The etalon parameters for this design are obtained using standard optimization techniques to reduce the group delay ripple for each channel. Other designs can be obtained by using similar techniques.

[0090] The front reflective coatings of the etalons are designed to match the reflectivity curves shown in FIG. 6A. The FSRs of the etalons are tuned to achieve the desired phase shift shown in FIG 6B. In one implementation, the basic setup is the one shown in FIG. 2. The wavelength-dependent reflectivity curve varies in the vertical direction but the free spectral range varies in the orthogonal, horizontal direction. Thus, tuning the point of incidence from 155B to 155C maintains the same reflectivity curve but adjusts the free spectral range. Conversely, tuning the point of incidence from 155B to 155A maintains the same free spectral range but adjusts the reflectivity. The etalon can also be designed so that the free spectral range and reflectivity vary in a coupled fashion.

[0091] Comparing FIG. 6B with FIG. 6A, the phase shift variation over wavelength is seen to be not as significant as the reflectivity variation over wavelength. Therefore, for some applications, a constant phase shift is acceptable and only the reflectivity varies with wavelength in order to compensate for dispersion slope. This simplifies the design and manufacture of the system.

[0092] The reflectivity curves shown in FIG. 6A are realized by proper design of the front reflective coating. Multiple solutions exist for the same reflectivity curve. In one solution, the system 10 shown in FIG. 1 consists of three etalons. The etalon material is BK7 glass. The front coating of each etalon consists of five layers of material. The recipe of each etalon's front coating is as follows:

- etalon 1, (1.330 TiO₂, 1.297 SiO₂, 1.512 TiO₂, 0.101 SiO₂, 0.139 Ta₂O₅).
- etalon 2, (1.808 Ta₂O₅, 1.371 SiO₂, 0.981 Ta₂O₅, 0.105 SiO₂, 0.126 Ta₂O₅).
- etalon 3, (1.781 Ta₂O₅, 1.602 Al₂O₃, 1.131 TiO₂, 0.131 SiO₂, 0.221 Ta₂O₅).

[0093] FIGS. 7A-7C show the reflective coefficient as a function of wavelength for these coatings. FIGS. 7A-7C are the reflectivity of etalon 1, etalon 2, and etalon 3, respectively. Different curves in each chart correspond to the reflectivity at different
thicknesses of the top layer. Curves 420A–420D correspond to thicknesses of 0%, 25%, 50% and 75% of the total thickness of the top coating layer. The thickness of the other coating layers is chosen to achieve the desired reflectivity slope, which in turn compensates for dispersion slope.

[0094] The reflectivity of the each etalon can be tuned by changing the point of incidence on the etalon. When the reflectivity is tuned, the slope of the reflectivity curve changes but the reflectivity value at the reference wavelength remains approximately constant, as shown in FIGS. 7A-7C. This is a useful characteristic for achieving tunable dispersion slope compensation, as it allows the dispersion slope to be tuned without introducing a significant dispersion offset. The reference wavelength is approximately 1550 nm which, in this example, may not be at the center of the wavelength bands.

[0095] The coating design shown in this example also produces a phase shift response. FIG. 7D shows the phase shift caused by the front coating of etalon 2. The other etalons have similar curves. The different curves 430A-430D correspond to different thicknesses of the top coating layer and correspond to the curves 420A-420D in FIGS. 7A-7C. Three effects can be observed in FIG. 7D. First, the phase shift is a linear function of wavelength. The linear phase shift can be compensated by FSR mismatch. Second, when the reflectivity slope is tuned (i.e., the point of incidence is tuned), the curve shifts up or down. This shift can be compensated by temperature tuning. Third, the slope of the phase shift curve does not change significantly when the reflectivity slope is tuned. Therefore, for many applications, there is no need to tune the FSR when the dispersion slope is tuned. This simplifies the device.

[0096] FIGS. 8A-8D shows the dispersion as a function of wavelength of this system. Curve 450 is the actual chromatic dispersion realized by the three-etalon system. Note that curve 450 is not a continuous curve. Each dot on curve 450 represents the chromatic dispersion value of the three-etalon system within the operating bandwidth for one of the wavelength channels. The complete set of dots represents the chromatic dispersion values for all of the wavelength channels. Curve 460 is the absolute error in the actual chromatic dispersion 450, as measured as a percentage of the ideal chromatic dispersion 440. This curve 460 has the same form as curve 450. The dots represent actual errors for each wavelength channel.
[0097] The dispersion slope of the system, using the coating designs discussed above, can be continuously tuned from 4 ps/nm² to -8.5 ps/nm². FIG. 8A illustrates a dispersion slope of -8.5 ps/nm², which compensates for 100km of LEAF fiber. Other dispersion slopes can be achieved by changing the point of incidence on each etalon. FIG. 8B shows a dispersion slope of -5 ps/nm² with a slight dispersion offset to -540 ps/nm at the reference wavelength. FIG. 8C has a dispersion slope of -1 ps/nm² and a dispersion of -575 ps/nm at the reference wavelength. The small dispersion deviation at the reference wavelength can be minimized by increasing the number of layers in the front reflective coating or by introducing a tunable dispersion offset to compensate. FIG. 8D shows an example with a positive dispersion slope of 3 ps/nm².

[0098] The three-etalon example discussed above is one possible solution among many. Other solutions which use different materials, different numbers of layers in the coating, and different thicknesses for the layers can also be used to tune dispersion slope without introducing a significant dispersion offset. Systems can also be designed to target a specific type of fiber. For example, the system can be designed so that the dispersion offset value and dispersion slope value are closely matched to the values required to compensate for a specific fiber of certain length. In other words, the dispersion offset and dispersion slope both change as the system is tuned.

[0099] FIGS. 9-10 illustrate various manners in which the reflectivity can vary over the front surface 112 of a variable reflectivity etalon. In FIG. 9A, the front reflective coating 120 includes a top layer 310 of material. The physical thickness of the top layer 310 varies according to location on the front surface 112. In one implementation, the top layer 310 has a constant refractive index and the optical thickness, which is the product of the refractive index and the physical thickness, varies over a range between zero and a quarter wave. In the case where the optical thickness of top layer 310 varies from zero to a quarter wave, the reflectivity will vary from minimum at zero thickness to maximum reflectivity at quarter wave thickness. More generally, the thickness varies over a quarter wave (i.e., from zero to a quarter wave, or from a quarter wave to a half wave, or from a half wave to three quarters wave, etc.), resulting in a monotonic variation of reflectivity with thickness.

[0100] In the example of FIG. 9A, the thickness of top layer 310 changes monotonically with the linear coordinate x and does not vary in the y direction (i.e., into or out of the
paper). If the optical thickness remains within a quarter wave range, the reflectivity of the front reflective coating 120 will also vary monotonically with $x$ but will be independent of $y$. The dispersion $D$ will also vary with $x$ and not with $y$.

[0101] The front reflective coating 120 is not restricted to a single layer design. FIG. 9B shows a front reflective coating 120 with multiple layers. In this example, additional layers of material 320A-320C are disposed between the top layer 310 and the front surface 112. In one implementation, these layers 320 are constant refractive index and constant physical thickness. For example, they can be quarter wave layers (or integer multiples of quarter waves). The top layer 310 has a variable physical thickness, as in FIG. 9A. In alternate embodiments, some or all of the intermediate layers 320 may also vary in thickness.

[0102] The etalons in FIGS. 9C and 9D are similar, except that the body 110 includes a gradient index material 111 bonded to a constant index material 113, as described previously.

[0103] In the examples of FIGS. 9, the reflectivity was a continuous function of location on the front surface. The thickness of top layer 310 varied continuously with the linear coordinate $x$. In FIG. 10, the front reflective coating 120 includes a top layer 415 of material that varies in physical thickness in a stepwise fashion. That is, layer 415 has a constant thickness over some finite region, a different constant thickness over a second region, etc. In FIG. 10, these regions are rectangular in shape, with a finite extent in $x$ but running the length of the etalon in $y$. However, they can be other shapes. For example, hexagonally-shaped regions are well matched in shape to circular beams and can be close packed to yield many different regions over a finite area.

[0104] Other variations of thickness as a function of position are possible. In this class of variable reflectivity etalons, the reflectivity of front reflective coating 120 is generally determined by the thickness of the coating (or of specific layers within the coating). Therefore, different reflectivity functions may be realized by implementing the corresponding thickness function. For example, reflectivity can be made a linear function of coordinate $x$ by implementing the corresponding thickness variation in the $x$ direction. The required thickness at each coordinate $x$ can be determined since the relationship between thickness and reflectivity is known, for example by using conventional thin film design
tools. The reflectivity and/or thickness can also vary according to other coordinates, including $y$, the polar coordinates $r$ and/or $\theta$, or as a two-dimensional function of coordinates.

[0105] FIGS. 22A-22B are graphs further illustrating the performance of variable reflectivity etalon 100. FIGS. 22A and 22B detail the performance of a 3-layer structure where the top layer 310 varies in thickness from zero to a quarter wave. However, the general phenomenon illustrated by FIGS. 22A and 22B are also applicable to reflective coatings with other numbers of layers. FIG. 22A graphs reflectivity $R$ as a function of thickness of top layer 310. The thickness is typically measured in reference to optical wavelength. Thus, a normalized optical thickness of 0.10 corresponds to a physical thickness that results in 0.10 wavelength. The normalized optical thickness of 0.00 corresponds to zero thickness and the normalized optical thickness of 0.25 corresponds to a quarter wave thickness. The reflectivity varies from 0%-40%. The range of reflectivities can be offset and/or expanded by adding more layers 320.

[0106] Referring again to the examples in FIGS. 9-10, these examples vary reflectivity by varying the optical thickness of the front reflective coating 120. However, varying the optical thickness also varies the phase of the OPL. This variation is not significant enough to substantially change the free spectral range of the etalon, so the basic periodicity of the etalon response essentially remains fixed. However, this phase variation is significant enough to affect the location of the peak of the etalon response. In other words, referring to FIGS. 3, the curves 210, 220 and 230 will shift slightly to the right or left with respect to each other as a result of the phase shift introduced by the finite thickness of front reflective coating 120.

[0107] FIG. 22B graphs this effect. Curve 2210 graphs the phase shift in OPL as a function of the layer thickness, which is normalized in wavelength. Curve 2220 graphs the corresponding wavelength shift of the spectral response as a function of the layer thickness, assuming a free spectral range of 50 GHz. For example, at a thickness of a quarter wave, the single layer coating introduces a phase shift of $\pi$ radians, which shifts the spectral response by 0.2 nm relative to the response at zero thickness.
[0108] In some cases, it is undesirable to have a phase shift (and corresponding shift of the spectral response). For example, it may be desirable for all of the spectral responses to have peaks and minima at the same wavelengths. In these cases, the phase shift caused by thickness variations in the front reflective coating 120 must be compensated for. In one approach, the transparent body 110 has an optical path length which varies with location, and the variation in the transparent body 110 compensates for the variation caused by the front reflective coating 120.

[0109] Referring to FIG. 9A, in one example embodiment, the front and back surfaces 112 and 114 of transparent body 110 are not exactly parallel. Rather, they are slightly tilted so that the body 110 is thicker at point 155B than at 155A, thus compensating for the thinner top layer 310 at point 155B.

[0110] FIGS. 11A-11C illustrate one method for manufacturing the etalon shown in FIG. 9. Basically, a top layer 310 of uniform thickness is first deposited on the front surface 112 of the etalon body 110. Then, different thicknesses of the top layer 310 are removed according to the location on the front surface. What remains is a top layer 310 of varying thickness.

[0111] In FIG. 11A, a uniform top layer 310 has already been deposited on the etalon body 110 using conventional techniques. The top layer 310 has also been coated with photoresist 710. The photoresist 710 is exposed 715 using a gray scale mask 720. Thus, the photoresist receives a variable exposure. In FIG. 11B, the photoresist 710 has been developed. The gray scale exposure results in a photoresist layer 710 of variable thickness. The device is then exposed to a reactive ion etch (RIE). In areas where there is thick photoresist, the etch removes all of the photoresist and a little of the top layer 310 of the front reflective coating. In areas where there is thin photoresist, the etch removes more of the top layer 310. The end result, shown in FIG. 11C is a top layer of varying thickness.

[0112] FIGS. 11A-11C illustrate a manufacturing process that uses reactive ion etching although other techniques can be used. For example, in a different approach, other uniform etching techniques or ion milling can be used to remove different thicknesses from the top layer 310. Mechanical polishing techniques or laser ablation may also be used. In one laser ablation approach, a laser is scanned across the top layer 310 and ablates different amounts of material at different locations. The result is a top layer 310 of varying thickness. In a
different approach, rather than depositing a top layer 310 of uniform thickness and then removing different amounts of the top layer, a top layer 310 of varying thickness is deposited. Finally, FIGS. 11A-11C describe the manufacture of the etalon in FIG. 9A. However, the techniques described can be used to manufacture other types of tunable etalons, including those shown in FIGS. 9-10.

[0113] FIGS. 12-16 illustrate different ways to translate the point of incidence of the optical beam 150. In all of these examples, the incoming optical signal is shown as arriving via an optical fiber 810 and collimated by a lens 820 to produce the optical beam 150. This is merely a pictorial representation of the input port 800 (labeled as input port 22 in FIG. 1) for optical beam 150. It is not meant to imply that other designs for the input/output ports cannot be used. For example, the optical beam 150 may arrive in a collimated form, the lens may be integrated onto the fiber, the fiber may be replaced by a waveguide, there may be other intermediate devices (e.g., mirrors, beamsplitters, optical filters), etc. Note that the input port 800 can also serve as the output port. In FIGS. 12-16, the optical signal is shown as arriving via fiber 810, collimated by lens 820, propagates through etalon 100, is recollected by lens 820 and exits via fiber 810.

[0114] FIG. 18 is a top view of an etalon stage that uses separate input and output fibers 810 and 811. In this device, the two fibers 810 and 811 are placed symmetrically about the optical axis of the collimating lens 820. Thus, the optical beam 150 will leave fiber 810, reflect through the etalon 100 and return to fiber 811. The optical beam 150 will not be exactly normally incident on the etalon 100. However, some deviation from normal incidence can be tolerated without significantly affecting the overall performance. A typical tolerance is that the beam is within 0.6° of normal to prevent significant effects due to beam walk off, although actual tolerances will depend on the application. The beam displacement approaches described in FIGS. 12-16 below are also generally applicable to the architecture shown in FIG. 18. One advantage of the dual fiber approach is that a circulator (or other similar device) is no longer required to separate the incoming and outgoing beams.

[0115] FIG. 17 is a top view of an etalon stage that utilizes a dual fiber collimator 820 and a free space circulator 36. In this device, two fibers 810 and 811 are coupled to a dual fiber collimator 820 which is coupled to the rest of the etalon stage by a free space circulator 36. Thus, an optical beam is input via fiber 810, is collimated by the dual fiber collimator 820
and then enters the remainder of the etalon stage. On the return trip, the optical beam enters
the circulator 36 from the opposite direction and, as a result, is directed to output fiber 811
rather than input fiber 810. As with FIG. 18, the beam displacement approaches described
in FIGS. 12-16 below are also generally applicable to the architecture shown in FIG. 17.
Advantages of this approach include reduced size and lower optical loss.

[0116] In FIGS. 12-13, beam displacement is achieved by creating relative movement
between the input port 800 and the tunable etalon 100. In FIG. 12, the input port 800 is
translated relative to a stationary tunable etalon 100. In particular, a mechanical actuator
830 moves the fiber 810 and collimating lens 820, thus moving the point of incidence.
More generally, an actuator which is physically connected to the input port 800 can be used
to translate the input port 800 relative to the etalon 100, thus changing the point of
incidence. In FIG. 13, a mechanical actuator 830 is connected to the etalon 100 and
translates the tunable etalon 100 relative to a stationary optical beam 150. In other
implementations, both the input port 800 and the etalon 100 can be moved simultaneously.

[0117] In FIGS. 14-16, the input port 800 and etalon 100 remain in fixed locations relative
to each other. A separate beam displacer 1010, 1110, 1210 is located in the optical path
between the input port 800 and etalon 100. The beam displacer is used to change the point
of incidence of the optical beam 150 to different locations on the etalon’s front surface
while maintaining normal incidence of the optical beam on the etalon’s front surface.

[0118] FIGS. 14A-14B are a perspective view and a top view of an etalon stage in which the
beam displacer 1010 is rotated in order to change the point of incidence. In this example,
the beam displacer 1010 includes a transparent body 1020 that has an input surface 1022
and an output surface 1024. The beam displacer 1010 is located in the optical path of the
optical beam 150 and rotates about an axis 1040 which is perpendicular to the direction of
propagation of the optical beam 150. In this example, the input and output surfaces 1022
and 1024 are plane-parallel to each other. In FIGS. 14, the optical beam 150 propagates in
the z direction, the reflectivity of etalon 100 varies in the x direction, and the axis of rotation
1040 is in the y direction.

[0119] The beam displacer 1010 operates as follows. The optical beam 150 enters the
transparent body 1020 through the input surface 1022 and exits the body 1020 through the
output surface 1024. Since the two surfaces 1022 and 1024 are parallel to each other, the exiting beam propagates in the same direction as the incoming beam, regardless of the rotation of the beam displacer 1010. As a result, the exiting beam always propagates in the z direction and the etalon 100 is oriented so that the beam 150 is normally incident upon it. Rotation of the beam displacer 1010 about the y axis produces a translation of the optical beam in the x direction due to refraction at the two surfaces 1022 and 1024. The reflectivity of the front reflective coating 120 also varies in the x direction. Thus, different reflectivities for etalon 100 can be realized by rotating the beam displacer 1010.

[0120] FIGS. 14 also show the etalon 100 as being mounted on a thermoelectric cooler 1050. The cooler 1050 is in thermal contact with the transparent body of the etalon 100 and is used to control the temperature of the etalon since the temperature affects the free spectral range and OPL tuning factor of the etalon. Other types of temperature controllers may be used in place of the thermoelectric cooler 1050.

[0121] In FIGS. 15A-15B, the beam displacers 1110A and 1110B are based on translatable reflective surfaces. Generally speaking, the optical beam 150 reflects off of at least one reflective surface en route to the etalon 100. By translating the reflective surface, the point of incidence for the optical beam 150 is moved but the normal incidence is maintained. In FIG. 15A, the beam displacer 1110A includes a right angle prism 1120 and the reflective surface is the hypotenuse 1122 of the prism. The optical beam 150 enters the prism, total internally reflects off the hypotenuse 1122 and exits the prism to the etalon 100. By translating the prism 1120, the point of incidence on the etalon can be moved. Note that the prism can be translated in many directions. For example, translating in either the x or z direction will result in movement of the point of incidence.

[0122] In FIG. 15B, the beam displacer 1110B includes a pair of mirrors 1130A-B. At each mirror 1130, the optical beam 150 reflects at a right angle. Translating the mirrors 1130 in the x direction moves the point of incidence.

[0123] The beam displacers shown in FIGS. 15 are merely examples. In both of these cases, mirrors and prisms (or other types of reflective surfaces) can be substituted for each other. Furthermore, it is not necessary that the reflections occur at right angles or that the prism be a right angle prism. Other geometries can be utilized.
In FIG. 16, the beam displacer 1210 is a MEMS mirror. In this example, the beam displacer 1210 has a number of mirrors that can be turned on and off electrically. By turning on different mirrors, the optical beam 150 is deflected to different points of incidence. More generally, the device has a number of states, each of which directs the optical beam 150 to a different location on the etalon’s front surface. Other technologies, including acousto-optics and electro-optics, can also be used.

For clarity, the figures for the above examples illustrate translation in one dimension but this is not meant to be limiting. The extension to two dimensions is straightforward. For example, FIGS. 12 and 13 depict translation by a physical actuator in one dimension. A second actuator can be added to provide translation in a second dimension. Alternately, one actuator can displace the input port in one direction, and another actuator can displace the etalon in an orthogonal direction, thus combining the two approaches in FIGS. 12 and 13. As another example, for the rotating beam displacer in FIG. 14, a second beam displacer rotating about an orthogonal axis can be added to provide two dimensional translation. Alternately, the beam displacer can be constructed so that the transparent body 1020 is rotatable about two different axes, for example by mounting the body 1020 on a gimbal.

FIGS. 19A and 19B are functional block diagrams of etalon stages 20 with separate input and output fibers. In both of these examples, the etalon stage 20 includes an input fiber 22, an output fiber 24, an etalon 30 and an optical system 40 that is located between the fibers and the etalon.

The two fibers 22 and 24 serve as the optical input and output to the etalon stage 20. The fibers 22, 24 are held in position by conventional techniques: for example spacers, blocks with positioning grooves or capillaries. The optical system 40 directs light from the input fiber 22 to the etalon 30 and back to the output fiber 24. The optical path 42 is free space. For convenience, the term “forward optical path” 42A will be used to refer to the optical path from the input fiber 22 to the etalon 30 and the term “return optical path” 42B to refer to the path from the etalon 30 to the output fiber 24.

A median plane 60 is defined by the fibers 22, 24 and the optical path 42. The median plane 60 is generally perpendicular to the plane formed by the fibers and optical path, and generally located midway between the fibers 22, 24 and to a lesser extent also
midway between the optical paths 42A, 42B. It may be geometrically non-planar if, for example, mirrors or other devices fold the optical path 42. The optical path 42 contains a central axis 43, which is the path traveled by the central ray from the input fiber 22 to the etalon 30 to the output fiber 24. The central axis 43 enters and exits the etalon 30 at a substantially normal angle.

[0129] In FIG. 19A, the optical system 40 is designed so that the central axis 43 crosses the median plane 60 at least once and also bends towards the median plane 60 at least once both in the forward direction (i.e., within the forward optical path 42A) and in the return direction (i.e., within the return optical path 42B). In contrast, in FIG. 19B, the central axes 43A, 43B do not cross the median plane 60 between the fibers 22, 24 and the etalon 30.

[0130] FIGS. 20A-20D shows different implementations of the optical system 40 of FIG. 19A. In these examples, only the central axis of the optical path is shown for clarity. The optical system 40 includes a collimating lens 46 and additional optics 48 located between the collimating lens 46 and the etalon 30. In the forward direction, the collimating lens 46 collimates the light from the input fiber 22. In the return direction, the collimating lens 46 couples collimated light into the output fiber 24. In FIGS. 20A-20C, the optical path 42 is symmetric about the median plane 60. That is, the return optical path 42B is a reciprocal (since the light is propagating in the opposite direction) mirror image of the forward optical path 42A. This is not a requirement – FIG. 20D shows an example of an asymmetric optical path – but symmetry typically results in certain performance and manufacturing advantages.

[0131] In FIGS. 20A and 20B, the optical paths have the same general shape. The central axis 43 leaves the input fiber 22 parallel to the median plane 60 and the light is diverging. The collimating lens 46 collimates the light. It also bends the central axis 43 towards the median plane 60 and the central axis 43 crosses the median plane 60. The optics 48 bends the central axis 43 back towards the median plane 60. The central axis 43 travels through the etalon 30, where it crosses the median plane again, and begins its return trip to the output fiber 24. The return trip is the reverse of the forward trip. The central axis 43 is bent back towards the median plane 60 by the optics 48. It crosses the median plane and is bent to be parallel to the median plane by the collimating lens 46. The collimating lens 46 also focuses the light into the output fiber 24.
[0132] In one implementation, the two fibers 22, 24 and the collimating lens 46 are constructed as a single unit, typically referred to as a dual fiber collimator. Gradient index lenses (GRIN lenses) are often used as the collimating lens 46. In addition, it is desirable that the collimating lens 46 be designed so that the optical path 42 has its minimum waist at the etalon 30. Typically, this minimizes the spot sizes within the system and reduces diffraction losses.

[0133] The etalon 30 typically has a narrow acceptance angle. The central axis 43 must enter and exit at a substantially normal angle of incidence. For example, a typical tolerance for the dispersion compensation example described below is that the central axis 43 is within zero to three degrees of normal, although actual tolerances will depend on the application. If the central axis 43 leaves the collimating lens 46 at an angle that is greater than this tolerance, then the additional optics 48 reduces this angle to a value that is within tolerance.

[0134] The etalon stage 20 has many advantages compared to other approaches. For example, the etalon stage 20 eliminates the use of a circulator, waveguide coupler, or other type of optical coupler. This, in turn, can eliminate the corresponding losses introduced by these other devices and can significantly reduce the cost of the etalon stage. In addition, the fiber assembly can be simplified since a conventional dual fiber collimator can be used. This is possible even if the angle of the central axis leaving the dual fiber collimator is too steep to be used directly with the etalon 30. The additional optics 48 reduces the angle to within the etalon’s tolerances. It can also extend the separation between the fibers and the etalon to allow placement of additional devices in between them (e.g. a beam displacer).

[0135] In FIG. 20A, the additional optics 48A are based on refractive wedges. In both the forward and the return direction, there is a wedge 48A with base oriented towards the median plane. That is, the wedges 48A are oriented to bend light towards the median plane. In FIG. 20A, the two wedges 48A are shown as different parts of a single device. However, they can also be implemented as separate devices.

[0136] In FIG. 20B, the additional optics 48B are based on mirrors. The central axis 43 is bent by reflection rather than refraction. In the geometry shown, if the central axis 43 makes approximately the same angle before reflection as it does after reflection, then the mirrors
48B will be facing and approximately parallel to the median plane 60. If they are not at exactly the same angle, then the mirrors 48B will be slightly tilted, as shown in FIG. 20B.

[0137] In FIG. 20C, the mirrors 48B of FIG. 20B are replaced by optics 48C that operate using total internal reflection (TIR). Basically, the central axis 43 enters a block of transparent material 48C, is totally internally reflected off of its faces 49 and then exits the block 48C. The TIR faces 49 take the place of the mirrors 48B. The design in FIG. 20C also illustrates multiple bendings. In the forward direction, the central axis 43 is bent two times by optics 48C and crosses the median plane 60 once between the bendings. Extending this concept, bending the central axis N times would result in N-1 crossings of the median plane. The multiple bending concepts can be implemented by many or all of the approaches discussed and is not limited to the TIR approach shown in FIG. 20C.

[0138] As a final example, FIG. 20D illustrates a more complex, asymmetric optical path. This variation of the wedge approach of FIG. 20A is used to illustrate the following. First, the optical path is asymmetric. For example, the collimating lens may be off center and, as a result, bends one central axis more than the other. Alternately, the fibers 22 and 24 may be slightly misaligned, resulting in a similar skew. Or the etalon stage may be intentionally designed to be asymmetric. In addition, the two wedges 48A have different powers and are located in different positions. Thus, while the central axis 43 enters and exits the etalon 30 at near normal incidence, it is not symmetric relative to the median plane 60. A mirror 63 is also used to fold the optical path, perhaps to achieve a compact size. As a result of these asymmetries, the median plane 60 also is not strictly planar. FIG. 20D is used to illustrate some of the variations that are possible. Other variations will be apparent. For example, more complex prisms may be used in the optics 48, with the optical path making one or more internal reflections within the prism. As another variant, the optics 48 may bend the central axis a different number of times in the forward direction as in the reverse direction.

[0139] FIG. 21 shows an example implementation of the optical system 40 of FIG. 19B. In this example, the optical system 40 includes two collimating lenses 46A and 46B, one for each fiber. Collimating lens 46A (i.e., the forward collimating lens) collimates the light exiting the input fiber 22. The return collimating lens 46B couples collimated light back into the output fiber 24. Additional optics 48 (optional) direct the light from input fiber 22 to etalon 30 to output fiber 24.
[0140] In the example of FIG. 21, mirrors 48D fold the optical path in free space in order to reduce the overall size of the system. This approach simplifies the optics involved to bend the optical beams, resulting in a more stable system. Prisms, wedges, and other devices can also be used. In addition, many of the principles illustrated in the examples of FIGS. 20A-20D are equally applicable to the basic design shown in FIG. 19B. For example, if the light leaves input fiber 22 at an angle that deviates too much from normal, optics 48 can be used to reduce this angle to within tolerance. As another example, the forward and return optical paths may or may not be mirror images of each other. As a final example, the fibers 22,24 and collimating lenses 46A,46B can be packaged together, for example as two separate single fiber collimators (as compared to the single dual fiber collimator of FIGS. 20A-20D).

[0141] Although the invention has been described in considerable detail with reference to certain preferred embodiments thereof, other embodiments will be apparent. Therefore, the scope of the appended claims should not be limited to the description of the preferred embodiments contained herein.
WHAT IS CLAIMED IS:

1. A dispersion compensation system comprising:
   a chain of at least one etalon stage, each etalon stage comprising:
       an input port;
       an output port;
       an optical path from the input port to the output port; and
       an etalon located in the optical path, the etalon having a front
dielectric
   reflective coating and a back dielectric reflective coating;

   wherein:
   the output port of one etalon stage is optically coupled to the input port of a
   next etalon stage in the chain;
   in at least one etalon stage, the front reflective coating of the etalon has a
   reflectivity that varies according to location and a point of incidence
   of the optical path on the front reflective coating is tunable; and
   a chromatic dispersion of the chain of etalon stages is substantially constant
   over an operating bandwidth.

2. The dispersion compensation system of claim 1 wherein the chromatic dispersion of
   the chain of etalon stages can be tuned by tuning the point of incidence of the optical path
   on the front reflective coating.

3. The dispersion compensation system of claim 1 wherein the front reflective coating
   comprises:
       a layer having a physical thickness that varies according to location.

4. The dispersion compensation system of claim 1 wherein:
   each etalon is characterized by a free spectral range that is approximately equal to a
   channel spacing defined by an ITU grid; and
   the operating bandwidth of the chain of etalon stages is at least 50% of the channel
   spacing defined by the ITU grid.

5. The dispersion compensation system of claim 1 wherein, in each of the etalon stages,
   a phase of the optical path in the etalon is variable.
6. The dispersion compensation system of claim 5 wherein each etalon stage further comprises:
   a temperature controller coupled to the etalon for controlling a temperature of the etalon, wherein varying the temperature of the etalon varies the phase of the optical path in the etalon.

7. A dispersion compensation system for compensating for chromatic dispersion within a plurality of evenly spaced wavelength channels, the dispersion compensation system comprising:
   a chain of at least one etalon stage, each etalon stage comprising:
      an input port;
      an output port;
      an optical path from the input port to the output port; and
      an etalon located in the optical path, the etalon having a front dielectric reflective coating and a back dielectric reflective coating;
   wherein:
      the output port of one etalon stage is optically coupled to the input port of a next etalon stage in the chain;
      in at least one etalon stage, the front reflective coating of the etalon has a wavelength-dependent reflectivity that varies according to location and a point of incidence of the optical path on the front reflective coating is tunable; and
      the chromatic dispersion of the chain of etalon stages substantially compensates for chromatic dispersion over an operating bandwidth within each wavelength channel and the chromatic dispersion varies over the plurality of wavelength channels.

8. The dispersion compensation system of claim 7 wherein:
   the variation of chromatic dispersion over the plurality of wavelength channels is characterized by a dispersion slope; and
   the chromatic dispersion of the chain of etalon stages substantially compensates for the dispersion slope.

9. The dispersion compensation system of claim 7 wherein:
the variation of chromatic dispersion over the plurality of wavelength channels is characterized by a dispersion slope; and
the chromatic dispersion of the chain of etalon stages across the plurality of wavelength channels can be tuned to substantially compensate for a range of dispersion slopes.

10. The dispersion compensation system of claim 9 wherein, for a range of points of incidence, the wavelength-dependent reflectivity slope varies but a reflectivity offset is approximately constant at a reference wavelength.

11. The dispersion compensation system of claim 9 wherein, for a range of dispersion slopes, the chromatic dispersion of the chain of etalon stages is approximately constant at a reference wavelength.

12. The dispersion compensation system of claim 7 wherein the front reflective coating comprises:
   a first layer having a physical thickness that varies according to location.

13. The dispersion compensation system of claim 12 wherein the front reflective coating comprises:
   a layer of constant physical thickness that is not a quarter wave thick.

14. The dispersion compensation system of claim 7 wherein, for the at least one etalon stage, a free spectral range of the etalon in the at least one etalon stage varies according to location.

15. The dispersion compensation system of claim 14 wherein the etalon in the at least one etalon stage includes a gradient index material having an optical path length that varies according to location.

16. The dispersion compensation system of claim 14 wherein, for the etalon in the at least one etalon stage:
   the wavelength-dependent reflectivity slope of the front reflective coating varies according to a first coordinate;
   the free spectral range varies according to a second coordinate; and
the first coordinate and the second coordinate are orthogonal.

17. A variable reflectivity etalon comprising:
   a transparent body having a first surface and a second surface that is substantially
   plane-parallel to the first surface;
   a second dielectric reflective coating disposed upon the second surface; and
   a first dielectric reflective coating disposed upon the first surface, the first reflective
   coating having a reflectivity that varies according to location on the first
   surface.

18. The variable reflectivity etalon of claim 17 wherein the first reflective coating
   comprises:
   a top layer having a physical thickness that varies according to location on the first
   surface and a refractive index that does not vary according to location on the first
   surface.

19. The variable reflectivity etalon of claim 17 wherein:
   the etalon is configured to receive an optical beam;
   the optical beam is normally incident upon the etalon's first surface at a point of
   incidence and the optical beam is characterized by a spot size at the point of
   incidence;
   each location on the etalon's first surface is characterized by a dispersion curve that
   depends on the reflectivity of the first reflective coating at that location; and
   the dispersion curve is substantially invariant over the spot size.

20. The variable reflectivity etalon of claim 17 wherein an optical path length of a round
    trip through the etalon does not vary with location on the first surface.

21. An etalon apparatus comprising:
    an input port for receiving an optical beam;
    a variable reflectivity etalon comprising:
    a transparent body having a first surface and a second surface that is
    substantially plane-parallel to the first surface;
    a second dielectric reflective coating disposed upon the second surface; and
a first dielectric reflective coating disposed upon the first surface, the first reflective coating having a reflectivity that varies according to location on the first surface; and

wherein the optical beam is normally incident upon the etalon at a point of incidence and the point of incidence is tunable.

22. The etalon apparatus of claim 21 further comprising:
a temperature controller coupled to the etalon for controlling a temperature of the etalon, wherein the temperature controller adjusts the temperature of the etalon to a point where a center wavelength of a spectral response of the etalon equals a predefined wavelength.

23. The etalon apparatus of claim 21 further comprising:
a beam displacer located in an optical path between the input port and the etalon, wherein the beam displacer translates a point of incidence of the optical beam to different locations on the etalon’s first surface while maintaining normal incidence of the optical beam on the etalon’s first surface, and the input port is in a fixed location relative to the etalon.

24. The etalon apparatus of claim 23 wherein the beam displacer comprises:
a second transparent body having an input surface and an output surface, wherein:
the optical beam enters the second transparent body through the input surface and exits the second transparent body through the output surface and directed to the etalon,
the second transparent body is rotatable about an axis perpendicular to a direction of propagation of the optical beam, and rotating the second transparent body about the axis translates the point of incidence to different locations on the etalon’s first surface.

25. A method for manufacturing an etalon with variable reflectivity, the method comprising:
holding a transparent body having a planar first surface so that the first surface is accessible; and
creating a first dielectric reflective coating on the first surface, the first reflective
coating having a reflectivity that varies according to location on the first
surface.

26. The method of claim 25 wherein creating a first dielectric reflective coating on the
first surface comprises:
   depositing a top layer of uniform thickness; and
   removing different thicknesses of the top layer according to location on the first
   surface.

27. The method of claim 25 wherein creating a first dielectric reflective coating on the
first surface comprises:
   depositing a top layer, wherein the top layer has different thicknesses according to
   location.

28. An etalon stage comprising:
   an input fiber;
   an output fiber;
   an etalon;
   an optical system that is located between the fibers and the etalon, for directing light
   along a free space forward optical path from the input fiber to the etalon and
   along a free space return optical path from the etalon to the output fiber.

29. The etalon stage of claim 28 wherein:
   the fibers and the optical paths define a median plane optically located midway
   between the fibers, the optical paths are characterized by a central axis, and
   the central axis enters and exits the etalon at a substantially normal angle;
   and
   along the forward optical path, the optical system reduces an angle between the
   central axis and the median plane.

30. The etalon stage of claim 28 wherein the optical system comprises:
   a collimating lens for collimating light exiting the input fiber and for coupling
   collimated light into the output fiber; wherein the input fiber, the output fiber
   and the collimating lens are packaged as a dual fiber collimator.
31. The etalon stage of claim 28 wherein the optical system comprises:
   a forward collimating lens for collimating light exiting the input fiber, wherein the
   input fiber and forward collimating lens are packaged as a single fiber
   collimator; and
   a return collimating lens for coupling collimated light into the output fiber, wherein
   the output fiber and return collimating lens are packaged as a separate fiber
   collimator.
FIG. 3A

FIG. 3B

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FIG. 5A

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<th>r_3</th>
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FIG. 5B

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FIG. 8A  Dispersion Offset: -500 ps/nm, Slope: -8.5 ps/nm²

FIG. 8B  Dispersion Offset: -540 ps/nm, Slope: -5 ps/nm²
FIG. 8C  Dispersion Offset: -575 ps/nm, Slope: -1 ps/nm²

FIG. 8D  Dispersion Offset: -560 ps/nm, Slope: -3 ps/nm²
EXPOSURE 715

GRAY SCALE MASK 720

PHOTORESIST 710
TOP LAYER 310
BODY 110

FIG. 11A

ETCH 725

FIG. 11B

FIG. 11C

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Reflectivity vs. Normalized Coating Thickness

FIG. 22A

Wavelength (Phase) Shift vs. Normalized Optical Thickness

FIG. 22B

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# INTERNATIONAL SEARCH REPORT

**PCT/US02/25346**

**A. CLASSIFICATION OF SUBJECT MATTER**

- IPC(7) : G01B 9/02
- US CL : 356/345, 352

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
- U.S. : 356/345, 352, 346

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
- USPTA; US-PGPUB; IPO; DERWENT; IBM TDB

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<tbody>
<tr>
<td>A</td>
<td>US 6,115,121 A (ERSKINE) 05 September 2000 (05.09.2000), column 5, lines 42-58 &amp; column 13, lines 32-67 &amp; column 18, lines 1-67 &amp; column 24 lines 7-54 &amp; column 28, lines 15-61 &amp; column 31, lines 5-59, figures 5b, 14, 15a and 31</td>
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- " Special categories of cited documents:
  - "A": document defining the general state of the art which is not considered to be of particular relevance
  - "E": earlier application or patent published on or after the international filing date
  - "L": document which may throw doubts on priority claims of another claim or other special reason (as specified)
  - "O": document referring to an oral disclosure, use, exhibition or other means
  - "P": document published prior to the international filing date but later than the priority date claimed
  - "X": later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
  - "Y": document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
  - "Z": document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
  - "&": document member of the same patent family

Date of the actual completion of the international search: 26 November 2002 (26.11.2002)

Date of mailing of the international search report: 15 JAN 2003

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