Title: REFERENCE ARTIFACT FOR OPTICAL GROUP DELAY AND CHROMATIC DISPERSION

Abstract: The reference artifact has an amplitude response that includes an attenuation line having an extremum at a center frequency. The reference artifact has either or both of a calibrated optical group delay and a calibrated chromatic dispersion at a calibration frequency in a calibration frequency range that extends about the center frequency. One or both of optical group delay and chromatic dispersion are measured by providing a reference artifact. The reference artifact has an amplitude response that includes an attenuation line having an extremum at a center frequency. Either or both of the optical group delay and the chromatic dispersion of the reference artifact is calibrated at a calibration frequency in a calibration frequency range that extends about the center frequency.
APPLICATION FOR PATENT

REFERENCE ARTIFACT FOR OPTICAL GROUP DELAY AND CHROMATIC DISPERSION

Technical Field

The invention relates to a reference artifact usable as an optical group delay standard or a chromatic dispersion standard.

Background of the Invention

To accommodate the increasing demand for optical communications bandwidth, the number of optical channels transmitted via a single optical fiber has substantially increased. This results in a smaller wavelength spacing between optical channels in optical transmission systems employing dense wavelength division multiplexed (DWDM). System components such as the optical fiber and optical filtering components are known to disperse optical signals temporally as the signals pass through the optical system, and the dispersion is frequency dependent. This is described, for example, by G. Lenz, B.J. Eggleton, C.R. Giles, C.K. Madsen and R.E. Slusher in *Dispersive Properties of Optical Filters for WDM Systems*, 34 IEEE J. QUANTUM ELEC., 1390-1402 (1998). To optimize data transmission, either or both of the optical group delay and chromatic dispersion properties of the components of an optical transmission system need to be thoroughly characterized.

The systems used to characterize chromatic dispersion or optical group delay are typically complex combinations of optical hardware and analysis algorithms. These combinations include many sources of measurement uncertainty that can lead to significant errors. Accordingly, a need exists for a method for verifying measurements of optical group delay and chromatic dispersion that would provide confidence in the accuracy of a particular set of measurements and that would also permit measurements made by different measuring entities to be reliably compared.

A reference artifact for optical group delay and chromatic dispersion would facilitate measurements of optical group delay and chromatic dispersion. Such reference artifact would allow such measurements to be exchanged easily among different measuring entities. Such reference artifact should have a stable and well-understood optical group delay and chromatic dispersion.

Reference artifacts for optical group delay and chromatic dispersion based on fiber Bragg gratings (FBG), dielectric filters and spools of optical fiber have been proposed. However, such reference artifacts suffer from instability due to environmental variations.
Moreover, merely handling such reference artifacts can change their optical group delay and chromatic dispersion with no outward evident indication of this change. Finally, the optical group delay and chromatic dispersion of such reference artifacts are difficult to predict accurately.

Thus, what is needed is a reference artifact for optical group delay and chromatic dispersion that has an optical group delay and chromatic dispersion that are reliable, repeatable and substantially independent of environmental conditions and handling. What is also needed is reference artifact whose optical group delay and chromatic dispersion can be theoretically predicted with high accuracy.

Summary of the Invention

The invention provides a reference artifact for either or both of optical group delay and chromatic dispersion. The reference artifact has an amplitude response that includes an attenuation line having an extremum at a center frequency. The reference artifact has either or both of a calibrated optical group delay and a calibrated chromatic dispersion at a calibration frequency in a calibration frequency range that extends about the center frequency.

The amplitude response of the reference artifact may be the result of the absorption of light by a gas or a solid, or the result of interference in an etalon.

The reference artifact may have either or both of a calibrated optical group delay and a calibrated chromatic dispersion at more than one calibration frequency, and its amplitude response may additionally or alternatively include more than one attenuation line.

The invention additionally provides a method of measuring one or both of optical group delay and chromatic dispersion. In the method, a reference artifact is provided. The reference artifact has an amplitude response that includes an attenuation line having an extremum at a center frequency. Either or both of the optical group delay and the chromatic dispersion of the reference artifact is calibrated at a calibration frequency in a calibration frequency range that extends about the center frequency.

Either or both of the optical group delay and the chromatic dispersion of the reference artifact may be calibrated by providing a standard reference artifact and comparing either or both of the optical group delay and the chromatic dispersion of the reference artifact with the respective one of the optical group delay and the chromatic dispersion of the standard reference artifact.

Either or both of the optical group delay and the chromatic dispersion of the reference artifact may be alternatively be calibrated by determining physical parameters of the reference artifact, calculating the amplitude response from the physical parameters and calculating either or both of the optical group delay and the chromatic dispersion from the calculated amplitude response.

Either or both of the optical group delay and the chromatic dispersion of the reference
artifact may be also be calibrated by measuring the amplitude response of the reference artifact, and calculating either or both of the optical group delay and the chromatic dispersion from the measured amplitude response.

The optical group delay may be calculated by determining, from the amplitude response, a phase shift at each one of a plurality of optical frequencies to generate a phase response. The slope of the phase response at the calibration frequency is determined to obtain the optical group delay at the calibration frequency.

The chromatic dispersion may be calculated by determining the slope of the phase response at each one of a plurality of optical frequencies to generate an optical group delay response. The slope of the optical group delay response at the calibration frequency is determined to obtain the chromatic dispersion at the calibration frequency.

**Brief Description of the Drawings**

Figure 1A is a schematic drawing of a reference artifact according to the invention.

Figure 1B is a graph showing the amplitude response of the reference artifact according to the invention.

Figure 1C is a graph showing the optical group delay of the reference artifact according to the invention.

Figure 2 is a block diagram showing use of reference artifact according to the invention to calibrate an optical group delay test system.

Figure 3A is a flow chart of a method according to the invention for measuring either or both of optical group delay and chromatic dispersion.

Figure 3B is a flow chart showing an example of the processing performed in process 152 of the method shown in Figure 3A.

Figure 3C is a flow chart showing a first example of the processing performed in process 154 of the method shown in Figure 3A.

Figure 3D is a flow chart showing an example of the processing performed in process 156 of the method shown in Figure 3A.

Figure 3E is a flow chart showing a second example of the processing performed in process 154 of the method shown in Figure 3A.

Figure 4 is a block diagram of an amplitude response test system that can be used to measure the amplitude response of the reference artifact according to the invention.

Figure 5 shows a first practical embodiment, based on a gas cell, of a reference artifact according to the invention.

Figure 6 shows a second practical embodiment, based on a solid absorber, of a reference artifact according to the invention.

Figure 7 shows a third practical embodiment, based on an etalon, of a reference artifact according to the invention.
Detailed Description of the Invention

The invention is based on the observation that an optical device having a amplitude response that includes an attenuation line has a stable wavelength-dependent optical group delay and chromatic dispersion in a range of optical frequencies disposed about the center frequency of the attenuation line and that such optical device can therefore be used as reference artifact for optical group delay and chromatic dispersion. The attenuation line is the result of a wavelength-dependent light attenuation mechanism such as optical absorption or optical interference. The invention is further based on the observation that the optical group delay, and, hence, the chromatic dispersion, of such reference artifact can be calculated from the amplitude response of the artifact. The amplitude response can be easily and precisely measured.

Figure 1A shows the reference artifact 100 according to the invention for optical group delay and chromatic dispersion. Exemplary embodiments of the reference artifact will be described below.

The reference artifact 100 receives incident light 102 and outputs light 104. The reference artifact has one or both of a calibrated optical group delay and a calibrated chromatic dispersion. Thus, light 104 has either or both of a calibrated optical group delay and a calibrated chromatic dispersion relative to light 102. The reference artifact additionally has an amplitude response, and the light 104 has an amplitude response relative to light 102.

Figure 1A shows the light 102 transmitted through the reference artifact and output as the light 104. Alternatively, the light 102 may be reflected by the reference artifact and output as the light 104.

Figure 1B shows the amplitude response 120 of the reference artifact 100. The amplitude response is a plot of the amplitude of the light 104 output by the reference artifact. The amplitude is plotted against the optical frequency of the light 102. In this example, the light 102 has a flat optical frequency response. The amplitude response includes the attenuation lines 124 and 125.

In the example shown in Figure 1B, the reference artifact 100 has either or both of a calibrated optical group delay and a calibrated chromatic dispersion at the calibration frequency 128 located within a calibration frequency range. The calibration frequency range extends above and below the center frequency of the attenuation line. The center frequency of the attenuation line is the frequency at which the amplitude response 120 exhibits an extremum. For example, the center frequency of the attenuation line 124 is shown at 128.

The calibration frequency range of the reference artifact 100 is defined as the optical frequency range in which the reference artifact has a calibrated optical group delay and/or a calibrated chromatic dispersion. The optical group delay and chromatic dispersion can easily be calibrated with high precision at calibration frequencies within the line width of the
attenuation line 124, and at frequencies near the line width. An appropriate measure of the line width of the attenuation line is the full width at half maximum (FWHM) of the attenuation line. As the difference between the calibration frequency and the center frequency of the attenuation line increases, it becomes progressively more difficult to calibrate the optical group delay and chromatic dispersion precisely. Thus, the precision with which the reference artifact is calibrated can be relaxed towards the extremes of the calibration frequency range. Alternatively, a more difficult and complex measurement method has to be used to determine the attenuation response so that the calibration precision can be maintained towards the extremes of the calibration frequency range.

While it is possible for the reference artifact 100 to have a defined calibration precision in a calibration frequency range that extends about the center frequency of the attenuation line by a few tens of times the line width, it is generally more practical to narrow the calibration frequency range to one in which the reference artifact can be easily calibrated. To provide an optical group delay or chromatic dispersion standard over a wide range of optical frequencies, it is more practical to have a number of reference artifacts that collectively cover the desired optical frequency range. Each of the reference artifacts is calibrated over a narrow calibration frequency range centered on an attenuation line. Alternatively, a single reference artifact having multiple attenuation lines can be used.

Figure 1C shows the optical group delay 130 of the reference artifact 100 over a range of optical frequencies corresponding to the range of optical frequencies shown in Figure 1B. The optical group delay of the reference artifact 100 can be calibrated at one or more calibration frequencies in a calibration frequency range that extends about the center frequency of the attenuation line. Depending on the accuracy required, the calibration frequency range may extend beyond that shown, as noted above. The optical group delay and chromatic dispersion of the reference artifact 100 are substantially independent of environmental conditions. Moreover, the optical group delay and chromatic dispersion will not change as the result of handling, mechanical shock and other physical factors.

Figure 2 shows the reference artifact 100 being used to calibrate the optical group delay test system 140 prior to the optical group delay test system being used to measure either or both of the optical group delay and the chromatic dispersion of optical devices whose optical group delay and/or chromatic dispersion is unknown. The reference artifact has either or both of a calibrated optical group delay and a calibrated chromatic dispersion at a calibration frequency equal to the operating optical frequency at which the optical group delay test system is to perform its measurements. Alternatively, the calibration frequency can differ from the operating optical frequency of the optical group delay test system. If the calibration frequency differs significantly from the operating frequency of the optical group delay test system, the optical group delay test system can be calibrated more accurately by using two reference artifacts having calibration frequencies above and below the operating frequency and
interpolating the results. Alternatively, a single reference artifact having two calibration frequencies spanning the operating frequency can be used.

The optical group delay test system 140 includes the light output 142 and the light input 144. The light output is arranged to deliver the light 102 to the reference artifact 100. The light input is arranged to receive the light 104 output by the reference artifact.

The optical group delay test system 140 is set to generate the light 102. The optical frequency of the light 102 is equal to or near the calibration frequency of the reference artifact 100, as described above. If the reference artifact 100 has multiple calibration frequencies, the frequency of the light 102 is equal to or near one of the calibration frequencies. The optical group delay test system measures the optical group delay of the reference artifact using the light 104 received from the reference artifact. The optical group delay measurement generates an optical group delay result. The optical group delay test system may additionally or alternatively measure the chromatic dispersion of the reference artifact 100. In this case, the optical group delay test system generates a chromatic dispersion result.

The optical group delay result generated by the optical group delay test system 140 is compared with the calibrated optical group delay of the reference artifact 100 to determine the error, if any, in the optical group delay result. If such error exists, the optical group delay test system can be adjusted to reduce the error to zero. The optical group delay test system can then be used to measure the optical group delay of the optical devices whose optical group delay is unknown. Alternatively, optical group delay results generated by the optical group delay test system 140 on optical devices whose optical group delay is unknown can be corrected to compensate for the optical group delay error measured using the reference artifact 100.

The chromatic dispersion result generated by the optical group delay test system 140 may additionally or alternatively be compared with the calibrated chromatic dispersion of the reference artifact 100 to determine the error, if any, in the chromatic dispersion result. If such error exists, the optical group delay test system can be adjusted to reduce the error to zero. The optical group delay test system can then be used to measure the chromatic dispersion of the optical devices whose chromatic dispersion is unknown. Alternatively, chromatic dispersion results generated by the optical group delay test system 140 on optical devices whose chromatic dispersion is unknown can be corrected to compensate for the chromatic dispersion error measured using the reference artifact 100.

The reference artifact 100 is shown in Figure 2 as transmitting the light 102 to generate the light 104 returned to the optical group delay test system 140. However, this is not critical to the invention. The reference artifact may reflect the light 102 to generate the light 104 returned to the optical group delay test system 140.

In the example shown, the light 102 is a collimated beam received at the reference artifact 100, and the light 104 is a collimated beam output by the reference artifact. However,
this is not critical to the invention. The light 102 may be delivered to the reference artifact by
an input optical fiber (not shown), and the light 104 output by the reference artifact may be
received by an output optical fiber (not shown). Other suitable light-guiding elements may be
used instead of the optical fibers. Suitable converging elements (not shown) may be interposed
between the optical fibers and the reference artifact. One of the converging elements
collimates the light 102 diverging from the input optical fiber to form a collimated beam. The
other of the converging elements receives the light 104 as a collimated beam and focuses the
light on the output optical fiber. As an alternative to collimating and focusing the light, one of
the converging elements may focus the light 102 at a focal point part-way along the optical
path through the reference artifact, and the other of the converging elements may re-focus the
light 104 diverging from this focal point onto the output optical fiber. The optical fibers may
be fitted with suitable connectors to enable them to be connected easily to test systems for
measuring optical group delay, chromatic dispersion and amplitude response.

The reference artifact 100 can be calibrated in a number of different ways. For
example, the reference artifact can be calibrated by calibrating an optical group delay test
system similar to the optical group delay test system 140 described above using a standard
reference artifact whose optical group delay and/or chromatic dispersion is stable and
accurately known. The calibrated optical group delay test system is then used to calibrate
either or both of the optical group delay and chromatic dispersion of the reference artifact
100.

As another example, the optical group delay and chromatic dispersion of the reference
artifact 100 depend on physical parameters of the reference artifact. These physical
parameters are set during manufacture, or can be measured during or after manufacture. The
measurable physical parameters can be measured in situ where the reference artifact is being
used. The reference artifact 100 can then be calibrated by calculating its amplitude response
from the above-mentioned physical parameters, and then calculating either or both of its
optical group delay and chromatic dispersion from the calculated amplitude response.

As a further example, the reference artifact 100 may be calibrated using the calibration
method 150 according to the invention shown in Figure 3A. In this calibration method, the
reference artifact is calibrated by measuring its amplitude response. An example of a
calibration system 160 suitable for measuring the amplitude response and calibrating the
reference artifact using the measured amplitude response is shown in Figure 4. Calibrating the
reference artifact by measuring its amplitude response enables the reference artifact to be
calibrated quickly, simply and using test equipment that is typically available in most locations
where the reference artifact is likely to be used. Thus, the reference artifact can be calibrated
at the location where it is being used.

Figure 4 shows the reference artifact 100 connected to the calibration system 160.
The calibration system includes the tunable light source 162, the detector 164, the amplitude
response tester 166 and computational device 168.

The tunable light source 162 is arranged to deliver the light 102 to the reference artifact 100. The detector 164 is arranged to receive the light 104 from the reference artifact.

The amplitude response tester 166 is electrically connected to the tunable light source to deliver the frequency control signal FC that sets the frequency of the light 102 generated by the tunable light source. The amplitude response tester is additionally electrically connected to receive the electrical signal ES generated by the detector 164. The amplitude response tester operates to record amplitude response data points. Each amplitude data point is composed of the frequency of the light 102 generated by the tunable light source 162 and the level of the electrical signal ES generated by the detector 164 in response to the light 104 at that frequency.

The amplitude response tester 166 additionally includes an output via which it delivers the amplitude response data points ARDP to the computational device 168. The computational device calculates either or both of the optical group delay and chromatic dispersion of the reference artifact 100 from the amplitude response represented by the amplitude response data points. The computational device may include an input (not shown) via which data specifying the calibration frequency can be input. The computational device may form part of the amplitude response tester.

The reference artifact 100 receives the light 102 from the tunable light source 162. The reference artifact transmits this light and outputs the transmitted light 104 to the detector 164. The detector generates the electrical signal ES monotonically related to the intensity of the light 104, and thus providing a measure of the intensity of the light 104 output by the reference artifact.

Figure 3A shows the method 150 according to the invention for calibrating at least the optical group delay of the reference artifact 100 by measuring its amplitude response. The method may be performed using the calibration system 160 described above with reference to Figure 4. The reference artifact is calibrated at at least one calibration frequency, described above.

In process 152, the amplitude response of the reference artifact 100 is measured over an optical frequency range.

In process 154, the optical group delay of the reference artifact 100 is calculated at the calibration frequency from the amplitude response measured in process 152.

The method 160 may additionally include the optional process 156. In process 156, the chromatic dispersion of the reference artifact 100 is calculated at the calibration frequency.

Figure 3B shows an example of the processing performed in process 152 to measure the amplitude response of the reference artifact 100. The amplitude response of the reference artifact is measured over a measurement frequency range. When the amplitude response can
be modeled accurately using a standard function, such as a Lorentzian function or a Gaussian function, the optical frequency range can be narrow. For example, the measurement frequency range can be the line width.

When the amplitude response is not capable of being modeled accurately using a standard function, the measurement frequency range may be substantially wider than the half line width to obtain the desired calibration precision. This is especially so when the calibration frequency differs substantially from the center frequency of the attenuation line. In this case, the measurement frequency range may extend as far from the center frequency as the amplitude response tester 160 is capable of accurately measuring the attenuation produced by the attenuation line. The measurement frequency range should at least extend from the center frequency of the attenuation through the calibration frequency to a frequency symmetrical with the center frequency about the calibration frequency. If a low calibration precision is acceptable, these measurement frequency ranges can be narrowed.

In process 170, the tunable light source 162 is set to generate the light 102 at an optical frequency \( f_{\text{min}} \) corresponding to the minimum of the above-mentioned measurement frequency range.

In process 171, the level of the electrical signal generated by the detector 164 in response to the light 104 output by the reference artifact 100 is measured. Such level measurement indicates the intensity of the light 104.

In process 172, an amplitude response data point is recorded. The amplitude response data point is composed of the optical frequency to which the tunable light source 162 is set and the measured level of the electrical signal generated by the detector 164 in response to the light 104.

In process 173, the optical frequency of the light generated by the tunable light source 162 is incremented.

In process 174, a test is performed to determine whether the frequency \( f \) to which the tunable light source has been set exceeds the maximum frequency \( f_{\text{max}} \) of the above-mentioned measurement frequency range.

A YES result in process 174 causes execution of process 152 to stop, and execution to advance to process 154, described above. A NO result causes execution to return to process 171, described above, to enable another amplitude response data point to be generated.

The processing just described may be modified in process 170 to set the tunable light source 162 initially to generate the light 102 at the maximum optical frequency \( f_{\text{max}} \) of the above-mentioned measurement frequency range. Then, in process 173 the frequency of the light 102 is decremented, and the test in process 174 determines whether the frequency of the light is less than the minimum optical frequency \( f_{\text{min}} \) of the above-mentioned measurement frequency range.
As a further alternative, the frequency of the light 102 generated by the tunable light source may swept instead of stepped, and the level of the electrical signal generated by the detector 164 may be measured continuously. In this case, amplitude response data points are generated at predetermined increments of the optical frequency of the light 102.

Methods different from that just described may be used to measure the amplitude response of the reference artifact 100. Moreover, the method just described may be practiced using a test system different from that shown in Figure 4.

Figure 3C shows an example of the processing performed in process 154 to determine the optical group delay of the reference artifact 100 from the amplitude response data points gathered in process 152. The processing may be performed by the computational device 168 shown in Figure 4, or by another computational device (not shown). The processing shown in Figure 3C will calibrate embodiments of the reference artifact in which the attenuation line can be accurately modeled using a Lorentzian function. A gas cell, to be described below with reference to Figure 5, in which there is negligible pressure broadening is an example of such a reference artifact. Another example of the processing performed in process 154 that has a more general application will be described below with reference to Figure 3E.

In process 175, a curve-fitting process is performed to determine the center frequency $\omega_0$, the half line width $\Delta \omega'$ and the attenuation parameter $\alpha_0$ from the amplitude response data points measured in process 152. The half line width $\Delta \omega'$ is one-half of the line width. The amplitude $\alpha(\omega)$ at angular frequency $\omega$ is defined by:

$$
\alpha(\omega) = \exp \left[ -\alpha_0 \left( \frac{1}{1 + \left( \frac{\omega - \omega_0}{\Delta \omega'} \right)^2} \right) + \frac{1}{1 + \left( \frac{\omega + \omega_0}{\Delta \omega'} \right)^2} \right]
$$

(1)

Curve fitting algorithms suitable for determining a center frequency, a half line width and an attenuation parameter, proportional to the maximum attenuation, from a set of amplitude response data points are known in the art and will therefore not be described here.

Processes 176-179 are then performed to generate phase response data points representing the phase response of the reference artifact 100. Each phase response data point is composed of a phase shift $\theta(\omega)$ and a corresponding optical frequency $\omega$.

In process 176, an initial value $\omega_{min}$ of the optical frequency $\omega$, less than the calibration frequency, is set. The optical frequency range between the minimum optical frequency $\omega_{min}$ and the maximum optical frequency $\omega_{max}$ is a portion of the optical frequency range between the minimum optical frequency $f_{min}$ and the maximum optical frequency $f_{max}$ of the above-mentioned measurement frequency range. The portion is sufficient in extent to define the phase response of the reference artifact 100. Alternatively, the optical frequency range between the minimum optical frequency $\omega_{min}$ and the maximum optical frequency $\omega_{max}$ may be
the same as the measurement frequency range.

In process 177, the phase shift \( \theta(\omega) \) at the optical frequency \( \omega \) is calculated and a phase response data point is recorded. The phase response data point is composed of the phase shift \( \theta(\omega) \) and the optical frequency \( \omega \). The phase shift is calculated from the parameters determined in process 175, i.e., the center frequency \( \omega_0 \), the half line width \( \Delta \omega' \) and the attenuation parameter \( \alpha_0 \). The phase shift \( \theta(\omega) \) at the optical frequency \( \omega \) is calculated using the expression:

\[
\theta(\omega) = 2\alpha_0 \omega \Delta \omega' \left( 1 + \frac{\omega^2 - \omega_0^2}{\Delta \omega'^2} \right) \left( 1 + \left( \frac{\omega - \omega_0}{\Delta \omega'} \right)^2 \right) \left( 1 + \left( \frac{\omega + \omega_0}{\Delta \omega'} \right)^2 \right)
\]

(2).

In process 178, the optical frequency \( \omega \) is incremented.

In process 179, a test is performed to determine whether the optical frequency \( \omega \) is greater than a maximum optical frequency \( \omega_{\text{max}} \) which is greater than the calibration frequency.

When the test result in process 179 is NO, execution returns to process 177, where phase shift data point is calculated. When the test result in process 179 is YES, execution advances to process 180.

In process 180, the slope of the phase response represented by the phase response data points calculated in processes 176-179 is determined to obtain the optical group delay of the reference artifact 100. The slope at the calibration frequency is determined to obtain the optical group delay at the calibration frequency. Algorithms to determine the slope at a point on a curve defined by a set of data points are known in the art and will therefore not be described here.

The optical frequencies \( \omega \) may coincide with the optical frequencies \( f \) used in process 152, but this is not critical. Moreover, none of the optical frequencies \( \omega \) need coincide with the calibration frequency, although such coincidence is convenient.

Figure 3D shows an example of the processing performed in process 156 to determine the chromatic dispersion of the reference artifact 100. The processing may be performed by the computational device 168 shown in Figure 4, or by another computational device. In this processing, the optical group delay at each of a number of optical frequencies disposed about the calibration frequency is calculated to generate a respective optical group delay data point. The optical group delay data points represent an optical group delay response. The slope of the optical group delay response at the calibration frequency is calculated to determine the chromatic dispersion at the calibration frequency.

In process 182, an initial value of the optical frequency \( g_{\text{init}} \) less than the calibration
frequency, is set. The optical frequency range between the minimum optical frequency \( g_{\text{min}} \) and the maximum optical frequency \( g_{\text{max}} \) is a portion of the optical frequency range between the minimum optical frequency \( f_{\text{min}} \) and the maximum optical frequency \( f_{\text{max}} \) of the above-mentioned measurement frequency range. The portion is sufficient in extent to define the optical group delay response of the reference artifact 100. Alternatively, the optical frequency range between the minimum optical frequency \( g_{\text{min}} \) and the maximum optical frequency \( g_{\text{max}} \) may be the same as the measurement frequency range.

In process 183, the slope of the phase response at the optical frequency \( g \) is calculated from the phase response data points determined in process 177, and an optical group delay data point is recorded. The slope of the phase response at the optical frequency \( g \) is the optical group delay at the optical frequency \( g \). The optical group delay \( \tau_{g}(g) \) and the optical frequency \( g \) constitute the optical group delay data point.

In process 184, the optical frequency \( g \) is incremented.

In process 185, a test is performed to determine whether the optical frequency \( g \) is greater than a maximum optical frequency \( g_{\text{max}} \), which is greater than the calibration frequency.

When the test result in process 185 is NO, execution returns to process 183, where another phase response slope calculation is performed to generate another optical group delay data point. When the test result in process 185 is YES, execution advances to process 186.

In process 186, the slope of the optical group delay response represented by the optical group delay data points determined in process 183 is then determined to obtain the chromatic dispersion. The slope of the optical group delay response at the calibration frequency is determined to obtain the chromatic dispersion at the calibration frequency.

The optical frequencies \( g \) may coincide with the optical frequencies \( f \) used in process 152, but this is not critical. Moreover, none of the optical frequencies \( g \) need coincide with the calibration frequency, although it such coincidence is convenient since the optical group delay at the calibration frequency would normally have to be calculated.

Figure 3E shows an alternative example of the processing that may be performed in process 154 to calculate the optical group delay of the reference artifact 100 from the amplitude response measured in process 152. This processing may be used regardless of whether the attenuation line is accurately modeled by a Lorentzian function. For example, the amplitude response of an etalon, to be described below with reference to Figure 7, includes attenuation lines that are not accurately modeled by a Lorentzian function. Equation (3) set forth below is used to calculate the phase shift \( \theta(\omega) \) of the reference artifact at the optical frequency \( \omega \):

\[
\theta(\omega)=\frac{\omega}{\pi} \int_{-\infty}^{\infty} \frac{\ln(\alpha(f))}{f^2 - \omega^2} \, df
\]  

(3)
In process 188, the optical frequency \( \omega \) is set to a value \( \omega_{\text{min}} \), which is less than the calibration frequency.

In process 189, the optical frequency \( f \) is set to a minimum value \( f_{\text{min}}(\omega) \), which is less than the value of the optical frequency \( \omega_{\text{min}} \). The optical frequency \( f \) is one of the optical frequencies at which an amplitude response data point was generated in process 152. The minimum value \( f_{\text{min}}(\omega) \) and maximum value \( f_{\text{max}}(\omega) \) of the optical frequency \( f \) for a given value of the optical frequency \( \omega \) are disposed substantially symmetrically in frequency about the optical frequency \( \omega \).

In process 190, the accumulator used to accumulate the results generated in successive iterations of process 192, to be described below, is cleared.

In process 191, the natural logarithm of the amplitude response at the optical frequency \( f \) is determined. The natural logarithm may be calculated, or may be determined using a look-up table or in some other way.

In process 192, the squares of the optical frequencies \( f \) and \( \omega \) are calculated, a difference between the squares is calculated and the natural logarithm determined in process 191 is divided by the difference. The square of the optical frequency \( \omega \) need only be calculated after the value of \( \omega \) has been changed in process 188 or 197.

In process 193, the quotient generated in process 192 is added to the accumulator.

In process 194, the optical frequency \( f \) is incremented.

In process 195, a test is performed to determine whether the optical frequency \( f \) is greater than a maximum optical frequency \( f_{\text{max}}(\omega) \), which is greater than the calibration frequency.

When the test result in process 195 is NO, execution returns to process 191, where the natural logarithm of the amplitude response at the new value of the optical frequency \( f \) is determined. When the test result in process 195 is YES, execution advances to process 196.

In process 196, the optical frequency \( \omega \) is divided by \( \pi \) to generate a quotient, and the contents of the accumulator are multiplied by the quotient to generate the phase shift \( \theta(\omega) \) at the optical frequency \( \omega \). The phase shift \( \theta(\omega) \) and its corresponding optical frequency \( \omega \) are recorded as a phase response data point. Again, the quotient of the optical frequency \( \omega \) and \( \pi \) need only be calculated after the value of \( \omega \) has been changed in process 188 or 197.

In process 197, the optical frequency \( \omega \) is incremented.

In process 198, a test is performed to determine whether the optical frequency \( \omega \) is greater than the maximum optical frequency \( \omega_{\text{max}} \), which is greater than the calibration frequency.

When the test result in process 198 is NO, execution returns to process 189 so that the phase shift at the new value of the optical frequency \( \omega \) can be calculated, and another phase response data point recorded. When the test result in process 198 is YES, execution
advances to process 199.

In process 199, the slope of the phase response represented by the phase response
data points recorded in successive iterations of process 196 is determined to obtain the optical
group delay of the reference artifact 100. The slope of the phase response at the calibration
frequency is determined to obtain the optical group delay at the calibration frequency.
Algorithms to determine the slope at a point on a curve defined by a set of data points are
known in the art and will therefore not be described here.

The method just described may be simplified so that the loop composed of processes
190-196 is performed for all values of the optical frequency \( f \) in the range \( f_{\text{max}}(\omega) \) to \( f_{\text{max}}(\omega) \) only
when the optical frequency \( \omega \) is equal to \( \omega_{\text{min}} \). For all other values of the optical frequency \( \omega \),
e.g., for the optical frequency \( \omega_{\text{opt}} \), the value of \( f_{\text{max}}(\omega_{\text{opt}}) \) is set in process 189, and processes
190-193 are performed once to calculate \( \ln(\alpha(f_{\text{max}}(\omega_{\text{opt}})))/((f_{\text{max}}(\omega_{\text{opt}}))^2 - \omega_{\text{opt}}^2) \). The sum
accumulated in the accumulator at the previous value of the optical frequency \( \omega \), i.e., \( \omega_{\text{opt}} \), is
adjusted by reducing the sum by the value of \( \ln(\alpha(f_{\text{min}}(\omega_{\text{opt}})))/((f_{\text{min}}(\omega_{\text{opt}}))^2 - \omega_{\text{opt}}^2) \), which has
previously been calculated, and increasing the sum by the newly-calculated value of
\( \ln(\alpha(f_{\text{max}}(\omega)))/((f_{\text{max}}(\omega))^2 - \omega_{\text{opt}}^2) \).

The calibration method has been described with reference to an example in which the
reference artifact 100 transmits the light 102 to generate the light 104. However, this is not
critical to the invention. The reference artifact may reflect the light 102 to generate the light
104.

Three practical embodiments of the reference artifact 100 will now be described with
reference to Figures 5, 6 and 7. Two of the embodiments are based on absorption and one
is based on interference.

Figure 5 shows an embodiment 200 of a reference artifact based on absorption of the
light 102 by a gas. The above-mentioned attenuation line in the amplitude response of the
reference artifact 200 is an absorption line resulting from the gas absorbing a narrow range
of frequencies of the light 102. Typically, the amplitude response includes more than one
absorption line.

The reference artifact 200 is composed of the gas cell 202 in which gas 204 is
enclosed by the cell 206. The cell is composed of the side wall 210 and the end walls 212
and 214. The end wall 212 includes the window 216 of a material that is transparent in the
optical frequency range of the light 102. Examples of suitable window materials for use in a
reference artifact for the range of optical frequencies used in long-distance optical communica-
tions, i.e., 1.3 - 1.62 \( \mu \text{m} \), include, but are not limited to, glass, fused quartz and sapphire.

Window materials suitable for use in other ranges of optical frequencies are known in the art.

The example of the reference artifact 200 shown operates by transmission, and the
end wall 214 includes the window 218 similar to the window 216. Alternatively, the reference
artifact 200 may operate by reflection. In this case, the end wall 214 is reflective, and lacks
the window 218. Alternatively, the gas cell 202 may include a reflector (not shown) independent of the end wall 214 and positioned to reflect the light 102 received through the window 216 back through the window 216 as the light 104. As a further alternative, the reference artifact may include the window 218, and an external reflector (not shown) positioned to reflect light output from the window 218 back through the window 218 for output from the window 216 as the light 104.

The side wall 210 and the end walls 212 and 214 may be made of the same material as the window 216. Alternatively, the side wall, part of the end wall 212 and the end wall 214 may be made of a different material, which need not be transparent. The embodiment of the gas cell 202 shown has a substantially circular cross section and therefore has a single side wall 210. However, this is not critical to the invention: the gas cell 202 may alternatively have a polygonal cross-sectional shape, and a corresponding number of side walls.

Part of the side wall 210 is cut away to show the gas 204 enclosed in the cell 206. The gas enclosed in the cell is a gas whose absorption spectrum includes absorption lines in the calibration frequency range of the reference artifact 200. In particular the gas has an absorption spectrum that includes an absorption line at or near the calibration frequency at which either or both of the optical group delay and chromatic dispersion of the reference artifact 200 is calibrated. An embodiment of a reference artifact 200 that has either or both of a calibrated optical group delay and a calibrated chromatic dispersion at a calibration frequency within the line width of an absorption line of the gas 204 will additionally provide either or both of optical group delay reference and a chromatic dispersion reference at calibration frequencies outside the line width.

Detailed information on the absorption spectra of many different molecular gases can be found in Gerhard Herzberg, MOLECULAR SPECTRA AND MOLECULAR STRUCTURE (3 VOLUME SET), 2nd ed., Krieger Publishing Co., 1992. This information can be used to choose the gas used as the gas 204 to provide the reference artifact 200 with an amplitude response that includes an absorption line at a particular optical frequency and, hence, a corresponding calibration frequency range. Examples of suitable gases include acetylene, methane and hydrogen cyanide. For example, the absorption spectrum of acetylene includes an absorption line with a center frequency of $1.972 \times 10^{14}$ Hz (equivalent to a wavelength of 1520.09 nm). This makes acetylene suitable for use in a gas cell-based reference artifact for measuring the optical group delay of long-distance infra-red communication systems.

Atomic gases have absorption spectra with absorption lines at frequencies different from those of molecular gases and can be used in a reference artifact having calibration frequency ranges centered on such optical frequencies. Finally, mixtures of gases can be used to provide the gas 204 with an absorption spectrum having an increased number of absorption lines, and, hence, the possibility of an increased number of calibration frequency ranges, or of a broadened calibration frequency range extending across several absorption lines.
The absorption of light by the reference artifact 200 depends on an absorption parameter $\alpha_0$ that in turn depends on the absorption cross-section $\sigma$ of the gas 204, the numerical density $\rho$ of the gas and the physical length $L$ of the optical path through the gas, i.e.:

$$\alpha_0 = \sigma \rho L \quad (4).$$

The length of the optical path depends on the physical length of the cell 206. For a given physical length, a reflective reference artifact has twice the optical path length than a transmissive reference artifact.

The product of the optical path length and the numerical density of the gas 204 is chosen to give an amplitude response that can be accurately measured, as described above. However, the numerical density of the gas in part determines the width of the absorption line: increasing the density of the gas increases the line width. The optical path length can be changed without changing the line width. Too short an optical path length gives an amplitude response in which the variation in amplitude at the absorption line is too small to characterize the absorption line accurately. Too long an optical path length results in too much absorption of light and, as a result, the intensity of light 104 being insufficient for the gas cell 202 to operate as a useable reference artifact. An optical path length that results in a maximum attenuation in the range from 5-20 dB gives results suitable for many applications.

In practical examples, the optical path length was in the range from about 10 mm to about 500 mm, depending on the absorption cross-section of the gas. In one practical example, the optical path length was 150 mm.

Construction of the gas cell 202 is simplified when the pressure of the gas 204 is about atmospheric pressure. Such a gas pressure means that the cell 206 need only be constructed to prevent ambient air from contaminating the gas 204, and does not have to be constructed to withstand a significant pressure differential, as it would have to be if the gas 204 were at a significant pressure above or below atmospheric. The above-mentioned gases are useable at atmospheric pressure with optical path lengths of the order of 150 mm. Pressures above and below atmospheric pressure can alternatively be used.

The pressure of the gas 204 is higher than that typically used in a gas cell intended for use as a frequency reference. It is desirable to minimize the gas pressure in a gas cell intended for use as a frequency reference to minimize the line width. In a gas cell used as the reference artifact 200, a broader line width can be beneficial because it increases the calibration frequency range of the reference artifact. However, pressure broadening diminishes the accuracy with which the amplitude response can be accurately modeled using a Lorentzian function. Such a reference artifact may therefore need to be calibrated using the method described above with reference to Figure 3E.

A low-pressure gas cell intended for use as a frequency reference can also have its optical group delay and/or chromatic dispersion calibrated and can be used as a reference
artifact.

Instead of measuring the amplitude response of the gas cell 202 in process 152 of the method described above with reference to Figure 3A, the amplitude response can be calculated. The pressure of the gas 204 in the gas cell can be measured, the optical path length of the gas cell can be measured, or is known, and the absorption cross-section of the gas 204 can be determined by looking it up in a table of physical constants. The absorption parameter $a_0$ can be calculated from these parameters using equation (4).

The frequency and shape of the absorption line of a defined gas at a given optical frequency are known and can be determined by looking them up in an appropriate reference resource. The amplitude response can then be calculated from the absorption parameter $a_0$ and the known shape of the absorption line. The calculation can additionally take into account the effect of the pressure of the gas on the shape of the absorption line. Then, one of the methods described above with reference to Figures 3C or 3E can be used to calculate the optical group delay of the reference artifact 200 from the calculated amplitude response, and the method described above with reference to Figure 3D can be used to calculate the chromatic dispersion.

Figure 6 shows an embodiment 300 of a reference artifact based on absorption of the light 102 by a solid. The above-mentioned attenuation line in the amplitude response of the reference artifact 300 is an absorption line resulting from the solid absorbing a narrow range of frequencies of the light 102. Typically, the amplitude response includes more than one absorption line.

The reference artifact 300 is composed of the solid absorber 302. The solid absorber includes the end surfaces 312 and 314. The end surface 312 receives the light 102.

The example of the reference artifact 300 shown operates by transmission, and the light 104 is output from the end surface 314. Alternatively, the reference artifact 300 may operate by reflection. In this case, the end surface 314 is disposed orthogonal to the optical axis of the solid absorber and supports a reflective layer (not shown). Alternatively, the reference artifact 300 may additionally include a reflector (not shown), independent of the end surface 314, and positioned to reflect light output by the end surface 314 back into the solid absorber. The solid absorber then outputs this light via the end surface 312 as the light 104.

The solid absorber 302 is composed of a crystalline or non-crystalline solid matrix material doped with a dopant. The dopant gives the solid absorber an absorption spectrum that includes at least one absorption line. The dopant chosen is that which creates the absorption line at or near the calibration frequency. Examples of the matrix material include lithium niobate, potassium lithium tantalate niobate, oxide and fluoride glasses, silica and silicon dioxide. Examples of the dopant include erbium, lanthanum, holmium, yttrium, neodymium and other rare earths. Other materials for the solid absorber include yttrium aluminum garnet and ZBLAN glass, a fluoride glass including zirconium, barium, lanthanum, aluminum and sodium.
Information on the transition frequencies of many dopants can be found on page 585 of FIBER OPTIC TEST & MEASUREMENT, ed. Dennis Derickson, Prentice Hall PTR (1998). This information can be used to choose a dopant that will create an absorption line at or near a desired calibration frequency.

The solid absorber 302 may be configured as a prism, as shown; for example, as a slab-shaped prism or as a rod-shaped prism. Alternatively, the solid absorber may be configured as a waveguide. For example, the glass used as the core material of a planar waveguide may be doped with a dopant that provides the core material with the amplitude response described above. As another example, the core of an optical fiber may be doped with a suitable dopant that provides the core with the amplitude response described above. An optical fiber with an erbium-doped glass core has an absorption line at a wavelength of 1.53 \( \mu m \), for example. Such optical fibers are used as optical amplifiers, and are widely available.

The absorption of light by the reference artifact 300 depends on an absorption parameter \( a_0 \) in a manner similar to the gas cell described above. The absorption parameter is the product of the absorption cross-section of the dopant, the numerical density of the dopant and the length of the optical path of the light through the solid absorber. The length of the optical path depends on the physical length of the solid absorber.

The absorption parameter \( \alpha_0 \) is chosen to give an amplitude response that can be accurately measured, as described above. An absorption parameter that is too small gives an amplitude response in which the variation in amplitude at the absorption line is too small to characterize the absorption line accurately. Too large a product results in too much absorption of light and, as a result, the intensity of light 104 being insufficient for the solid absorber 302 to operate as a useable reference artifact.

Instead of measuring the amplitude response of the solid absorber 302 in process 152 of the method described above with reference to Figure 3A, the amplitude response can be calculated. The numerical density of the dopant is also known, or can be measured, the optical path length in the solid absorber can be measured, or is known, and the absorption cross-section of the dopant can be determined by looking it up in a table of physical constants. The absorption parameter \( \alpha_0 \) can be calculated from these parameters using equation (4). The frequency and shape of the absorption line caused by a defined dopant at a given optical frequency are known and can be determined by looking them up in an appropriate reference resource. The amplitude response of the solid absorber can then be calculated from the absorption parameter \( \alpha_0 \) and the known shape of the absorption line.

Figure 7 shows an embodiment 400 of a reference artifact based on interference. The above-mentioned attenuation line in the amplitude response of the reference artifact 400 is an interference line resulting from interference at certain frequencies of the light 102.

The reference artifact 400 is composed of the etalon 402. Etalons are known in the
art, are commercially available and may be used as or instead of the example shown. Accordingly, the example of the etalon 402 shown will only be briefly described.

The etalon 402 is composed of the parallel, semi-reflective surfaces 404 and 406 supported by the transparent substrates 414 and 416, respectively. The semi-reflective surfaces are separated from one another by a distance related to the center frequency of the interference line. The semi-reflective surfaces 404 and 406 are layers of metallic or dielectric material deposited on the surfaces 424 and 426, respectively, of the transparent substrates. The surfaces 434 and 436 of the transparent substrates remote from the surfaces 424 and 426 are non-parallel to the semi-reflective surfaces 404 and 406 and to one another, and are coated with an anti-reflective coating (not shown). These measures reduce the effect of the surfaces 434 and 436 on the interference characteristics of the etalon 402. Results acceptable for some applications can be obtained with surfaces 434 and 436 non-coated and parallel to the semi-reflective surfaces 404 and 406.

The distance between the semi-reflective surfaces 404 and 406 is defined by the spacer 418. The gap 420 between the semi-reflective surfaces may be evacuated, filled with gas, such as air, or filled with a solid or liquid material. When the gap is filled with a solid material, the spacer may be dispensed with. The gap material may also be used to support the reflective surfaces 404 and 406, in which case, the substrates 414 and 416 and the spacer 418 may be omitted.

The light 102 is received at the semi-reflective surface 404. Part of the light 102 is transmitted towards the semi-reflective surface 406. Part of the light received at the semi-reflective surface 406 is transmitted as the light 104. The remainder of the light received at the semi-reflective surface 406 is reflected back towards the semi-reflective surface 404. When the optical path length between the semi-reflective surfaces is an odd number of half-wavelengths of the light 102, the light received at the semi-reflective surface 404 is out of phase with the light transmitted by the semi-reflective surface 404, and destructive interference takes place. Thus, the intensity of the light that reaches the semi-reflective surface 406 is reduced at this frequency. To obtain an interference line at a given optical frequency, the spacing between the reflective surfaces, defined by the thickness of the spacer 418 in the example shown, is set to be equal to an odd number of quarter wavelengths at the desired optical frequency.

The center frequency of the interference line may be varied by varying the spacing between the reflective surfaces 404 and 406 or varying the refractive index of the material in the gap 420 between the reflective surfaces. For example, the pressure of air or another gas in the gap may be varied.

The example of the reference artifact 400 shown operates by transmission, and the semi-reflective surface 406 outputs the light 104. Alternatively, the reference artifact 400 may operate by reflection. In this case, the surface 406 is fully reflective. Alternatively, the
reference artifact 400 may additionally include a reflector (not shown), independent of the surface 404 and 406, and positioned to reflect light output by the semi-reflective surface 406 back into the etalon 402. The etalon then outputs this light via the semi-reflective surface 404 as the light 104.

The attenuation response of the etalon 402 depends on the reflectivity of the reflective surfaces 404 and 406: the greater the reflectivity, the greater the attenuation at the center frequency and the narrower the line width. A reflectivity that is too small gives an amplitude response in which the variation in amplitude at the interference line is too small to characterize the interference line accurately. Too large a reflectivity results in too much of the light 102 being reflected before entering the etalon, and, hence, the intensity of light 104 being insufficient for the etalon 402 to operate as a useable reference artifact.

Instead of measuring the amplitude response of the etalon 402 in process 152 of the method described above with reference to Figure 3A, the amplitude response can be calculated. The reflectivity of the reflective surfaces 404 and 406 is known, or can be measured, and the spacing between the reflective surfaces is known, or can be measured.

The frequency and shape of the attenuation line resulting from interference between light reflected by reflective surfaces is known and can be determined by looking it up in an appropriate reference resource. The amplitude response of the etalon can then be calculated from the reflectivities, the spacing and the known shape of the attenuation line.

Although this disclosure describes illustrative embodiments of the invention in detail, it is to be understood that the invention is not limited to the precise embodiments described, and that various modifications may be practiced within the scope of the invention defined by the appended claims.
We claim:

1. A reference artifact for at least one of optical group delay and chromatic dispersion, the reference artifact having an amplitude response including an attenuation line having an extremum at a center frequency, the reference artifact having at least one of (a) a calibrated optical group delay and (b) a calibrated chromatic dispersion at a calibration frequency in a calibration frequency range that extends about the center frequency.

2. The reference artifact of claim 1, in which the calibration frequency is equal to the center frequency.

3. The reference artifact of claim 1, in which the calibration frequency differs from the center frequency.

4. The reference artifact of claim 3, in which:
   the attenuation line additionally has a line width; and
   the calibration frequency lies outside the line width of the attenuation line.

5. The reference artifact of claim 1, comprising a gas cell.

6. The reference artifact of claim 1, comprising a solid absorber.

7. The reference artifact of claim 1, comprising an etalon.

8. The reference artifact of claim 1, in which the reference artifact has a at least one of (a) a calibrated optical group delay and (b) a calibrated chromatic dispersion at each of more than one calibration frequency.

9. The reference artifact of claim 1, in which the amplitude response includes more than one attenuation line.

10. A method of measuring at least one of (a) optical group delay and (b) chromatic dispersion, the method comprising:
   providing a reference artifact having an amplitude response including an attenuation line having an extremum at a center frequency; and
   calibrating the at least one of the optical group delay and the chromatic dispersion of the reference artifact at a calibration frequency in a calibration frequency range that extends about the center frequency.
11. The method of claim 10, in which calibrating the at least one of the optical group delay and the chromatic dispersion includes:
   providing a standard reference artifact; and
   comparing the at least one of the optical group delay and the chromatic dispersion of the reference artifact with the respective one of the optical group delay and the chromatic dispersion of the standard reference artifact.

12. The method of claim 10, in which calibrating the at least one of the optical group delay and the chromatic dispersion includes:
   determining physical parameters of the reference artifact;
   calculating the amplitude response from the physical parameters; and
   calculating the at least one of the optical group delay and the chromatic dispersion from the calculated amplitude response.

13. The method of claim 10, in which calibrating the at least one of the optical group delay and the chromatic dispersion includes:
   measuring the amplitude response of the reference artifact; and
   calculating the at least one of the optical group delay and the chromatic dispersion from the measured amplitude response.

14. The method of claim 13, in which:
   in providing the reference artifact, the attenuation line additionally has a line width; and
   measuring the amplitude response of the reference artifact includes measuring the amplitude response in a measurement frequency range encompassing at least part of the line width.

15. The method of claim 13, in which calculating the at least one of the optical group delay and the chromatic dispersion includes:
   determining, from the amplitude response, a phase shift at each one of a plurality of optical frequencies to generate a phase response; and
   determining the slope of the phase response at the calibration frequency to obtain the optical group delay at the calibration frequency.
16. The method of claim 15, in which calculating the chromatic dispersion includes:

- determining the slope of the phase response at each one of a plurality of optical frequencies to generate an optical group delay response; and
- determining the slope of the optical group delay response at the calibration frequency to obtain the chromatic dispersion at the calibration frequency.

17. The method of claim 16, in which determining the phase shift at each one of the plurality of optical frequencies includes summing, for multiple ones of an optical frequency, a quotient of a natural logarithm of an amplitude at the optical frequency and a difference between a square of the optical frequency and a square of the one of the plurality of the optical frequencies.

18. The method of claim 15, in which determining the phase shift at each one of the plurality of optical frequencies includes:

- determining the line width, the center frequency and an attenuation parameter from the measured amplitude response;

- calculating the phase shift from the center frequency, the line width, the attenuation parameter and the one of the optical frequencies.

19. The method of claim 10, in which, in providing a reference artifact, a gas cell is provided.

20. The method of claim 10, in which, in providing a reference artifact, a solid absorber is provided.

21. The method of claim 10, in which, in providing a reference artifact, an etalon is provided.

22. The method of claim 10, in which, in providing a reference artifact, a reference artifact having an amplitude response including more than one attenuation line is provided.
MEASURE AMPLITUDE RESPONSE OF OPTICAL GROUP DELAY STANDARD OVER AN OPTICAL FREQUENCY RANGE

CALCULATE OPTICAL GROUP DELAY AT CALIBRATION FREQUENCY FROM MEASURED AMPLITUDE RESPONSE

CALCULATE CHROMATIC DISPERSION AT CALIBRATION FREQUENCY

FIG. 3A

SET TUNABLE LIGHT SOURCE SET TO GENERATE LIGHT AT OPTICAL FREQUENCY $f_{\text{min}}$ CORRESPONDING TO MINIMUM OF MEASUREMENT FREQUENCY RANGE

MEASURE LEVEL OF ELECTRICAL SIGNAL GENERATED BY DETECTOR IN RESPONSE TO LIGHT OUTPUT BY OPTICAL GROUP DELAY STANDARD

RECORD AMPLITUDE RESPONSE DATA POINT

INCREMENT FREQUENCY OF LIGHT GENERATED BY TUNABLE LIGHT SOURCE

$f > f_{\text{max}}$?

STOP

FIG. 3B
PERFORM CURVE-FITTING PROCESS TO DETERMINE CENTER FREQUENCY $\omega_p$, HALF LINE WIDTH $\Delta \omega'$ AND ATTENUATION PARAMETER $\alpha_0$ FROM MEASURED AMPLITUDE RESPONSE DATA POINTS.

SET INITIAL VALUE OF OPTICAL FREQUENCY $\omega$

CALCULATE PHASE SHIFT $\theta(\omega)$ AT OPTICAL FREQUENCY $\omega$ FROM CENTER FREQUENCY $\omega_0$, HALF LINE WIDTH $\Delta \omega'$ AND ATTENUATION PARAMETER $\alpha_0$

INCREMENT OPTICAL FREQUENCY $\omega$

$\omega > \omega_{\text{max}}$?

CALCULATE SLOPE OF PHASE RESPONSE AT CALIBRATION FREQUENCY

FIG. 3C

SET INITIAL VALUE OF OPTICAL FREQUENCY $g$

CALCULATE SLOPE OF PHASE RESPONSE AT OPTICAL FREQUENCY TO GENERATE OPTICAL GROUP DELAY DATA POINT

INCREMENT OPTICAL FREQUENCY $g$

$g > g_{\text{max}}$?

CALCULATE SLOPE OF OPTICAL GROUP DELAY RESPONSE AT CALIBRATION FREQUENCY TO GENERATE CHROMATIC DISPERSION

FIG. 3D
SET INITIAL VALUE OF OPTICAL FREQUENCY $\omega_{\text{min}}$

SET INITIAL VALUE OF OPTICAL FREQUENCY $f_{\text{min}}(\omega)$

CLEAR ACCUMULATOR

DETERMINE $\ln(\alpha(f))$

CALCULATE $\{\ln(\alpha(f))\}/(f^2 - \omega^2)$

ADD QUOTIENT TO ACCUMULATOR

INCREMENT OPTICAL FREQUENCY $f$

$f > f_{\text{max}}$?

MULTIPLY ACCUMULATOR CONTENTS BY $\omega/\pi$ & OUTPUT RESULT AS $\theta(\omega)$

INCREMENT OPTICAL FREQUENCY $\omega$

$\omega > \omega_{\text{max}}$?

CALCULATE SLOPE OF PHASE RESPONSE AT CALIBRATION FREQUENCY TO GENERATE OPTICAL GROUP DELAY

FIG. 3E
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 GO1M11/00

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)
IPC 7 GO1M

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 practical, search terms used)
WPI Data, EPO-Internal, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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<tr>
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<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
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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 document published on or after the international filing date
  *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation 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

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  *X* 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
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Date of the actual completion of the international search: 25 March 2002

Date of mailing of the international search report: 03/04/2002

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Form PCT/ISA/2/10 (second sheet) (July 1992)
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