White-light spectral interferometry with the equalization wavelength determination used to measure distances and displacements

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Two new white-light interferometric techniques employing a low-resolution spectrometer in the equalization wavelength determination are proposed to measure distances and displacements. The techniques use a dispersive Michelson interferometer alone or a tandem configuration of a non-dispersive Michelson interferometer and a two-mode optical fibre when the dispersion in the interferometer and the intermodal dispersion in the optical fibre are known. We demonstrate experimentally that these known dispersions affect the range of measurable distances and the sensitivity of the displacement measurements.

1. Introduction

White-light spectral-domain interferometric techniques with channelled spectrum detection are well-established techniques that have been used in various optical measurements, including distance and displacement measurements [1]–[5], optical profilometry [6]–[8], and dispersion characterizing optical specimens [9]–[11]. However, it is well known that a white-light channelled spectrum interferometer, for example, can be operated in a limited range of distances with the minimum distance given by the spectral bandwidth of the white-light source and the maximum distance given by the spectrometer resolving power. Recently, we have demonstrated experimentally that two new techniques employing a low-resolution spectrometer and based on the equalization wavelength determinations can be used in substantially larger range of distances [12], [13]. These two new techniques, which need no phase retrieving procedure to be applied, have been used to measure the group refractive index dispersion in fused-silica samples [12] and the intermodal dispersion in optical fibres [13]. The group refractive index dispersion in fused-silica samples is measured in the uncompensated (dispersive) Michelson interferometer via the equalization wavelength determination as a function of the displacement in the interferometer. The equalization wavelength is in this case a wavelength at which the group optical path difference (OPD) between beams in the interferometer is zero. The intermodal dispersion in a two-mode optical fibre is measured in its tandem configuration with the compensated (non-dispersive) Michelson interferometer via the equalization wavelength determination as a function of the displacement in the interferometer.

It is evident that the equalization wavelength determination can also be used to measure distances and displacements when the dispersion in the interferometer is known. A range of measurable distances and the sensitivity of the displacement measurements can be varied with the thickness of a sample inserted in the interferometer. When the range of the distances is still narrow, a tandem configuration of non-dispersive and dispersive two-beam interferometers can be used to enlarge it. In this tandem configuration the equalization wavelength is a wavelength at which the OPD between beams in the first interferometer is the same as the group OPD between beams in the second interferometer. It is evident that the second (dispersive) interferometer can be effectively replaced by a two-mode optical fibre and the equalization wavelength determination can be used to measure the distances and displacements when the intermodal dispersion in the optical fibre is known.

In this paper the two new white-light interferometric techniques with the equalization wavelength determination are proposed to measure the distances or the displacements. The first interferometric technique uses a dispersive Michelson interferometer with the known dispersion. On two different examples we show that the range of measurable distances and the sensitivity of the displacement measurements are affected by the group refractive indices of the beamsplitter and sample, and by their thicknesses. The second interferometric technique uses a tandem configuration of a non-dispersive Michelson interferometer and a two-mode optical fibre with the known intermodal dispersion. On two different examples with two different optical fibres we show that the range of measurable distances and the sensitivity of the displacement measurements depend on the fibre intermodal dispersion.

2. Standard spectral-domain interferometric technique

In a standard spectral-domain interferometric technique with channelled spectrum detection, the recorded spectral interferograms are processed to obtain the OPDs between the interfering beams or the distances [1]–[4]. When a spectral-domain two-beam interference experiment with a compensated Michelson interferometer and a low-resolution spectrometer is considered [13], the spectral fringe visibility as a function of the distance L, which is the difference between the two arms of the interferometer, is given by

$$V(L) = \exp\left[-\left(\frac{\pi\Delta\nu_R}{\sqrt{\ln 2}}\frac{L}{c}\right)^2\right] \tag{1}$$

where $\Delta\nu_R$ the FWHM of the normalized Gaussian response function of the spectrometer and c is the speed of light. The maximum working distance L_{max} is limited by the lowest visibility $V_{min} = V(L_{max})$ below which the spectral interference fringes cannot be resolved. If we accept $V_{min} = 0.1$, Eq. (1) gives

$$L_{max} = \frac{\sqrt{\ln 2 \ln 10}}{\pi} \frac{c}{\Delta \nu_R} = \frac{\sqrt{\ln 2 \ln 10}}{\pi} \frac{\lambda^2}{\Delta \lambda_R} \approx 0.40 \frac{\lambda^2}{\Delta \lambda_R} \tag{2}$$

where $\Delta\lambda_R$ is the FWHM in wavelength domain. In our two-beam interference experiment with a low-resolution fibre-optic spectrometer [14] we had $\lambda = 694$ nm and $\Delta\lambda_R = 2$ nm so that L_{max} was approximately 95 μm. This value, which is in good agreement with that obtained experimentally, defines the range of the distances that can be measured using this standard spectral-domain interferometric technique.

3. New spectral-domain interferometric techniques

Two new spectral-domain interferometric techniques with the equalization wavelength determinations that employ a low-resolution spectrometer can be proposed to measure distances and displacements in enlarged ranges. The first technique uses a dispersive Michelson interferometer with a sample and the second technique uses a tandem configuration of a non-dispersive Michelson interferometer and a two -mode optical fibre.

3.1. Dispersive Michelson interferometer with a sample

If a dispersive Michelson interferometer as that shown in Fig. 1 includes a beamsplitter and a sample of the same dispersion, the group OPD $\Delta^g_M(\lambda)$ between beams at the output of the interferometer is given by

$$\Delta^g_M(\lambda) = 2l + N(\lambda)2(t_{eff} - t) \tag{3}$$

where $2l$ is the difference of the optical path lengths of both beams in the air, $N(\lambda)$ is the group refractive index of the beamsplitter and of the sample, and $2(t_{eff} - t)$ is

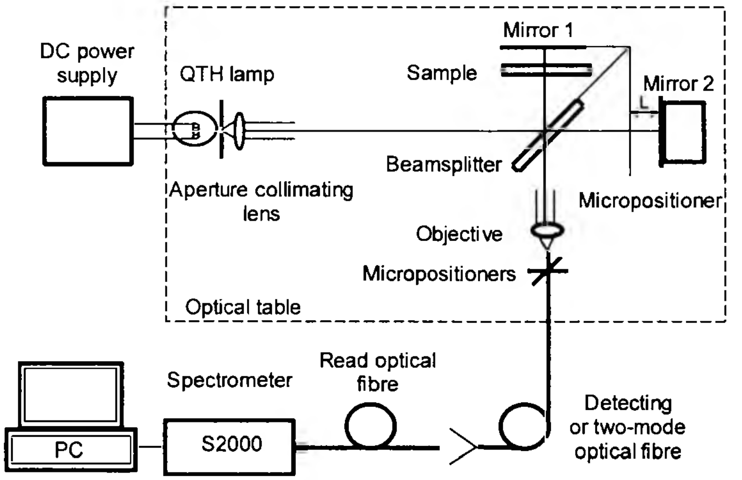

Fig. 1. Experimental set-up with a Michelson interferometer and a low-resolution spectrometer S2000.

the difference of the optical path lengths of both beams in the beamsplitter and in the sample (t_{eff} is the effective thickness of the beamsplitter and t is the thickness of the sample). We can introduce a suitable optical path lengths difference $l = l_0$ for which the Michelson interferometer is balanced, and which is connected with a suitable wavelength λ_0 of the source radiation. Moreover we can introduce the equalization wavelength λ_{eq}, for which the group OPD $\Delta^g_M(\lambda_{eq})$ is zero so that only in its vicinity the spectral interference fringes are resolved by a low-resolution spectrometer [12]. Equation (3) then gives for the distance $L = l - l_0$

$$L(\lambda_{eq}) = [N(\lambda_0) - N(\lambda_{eq})](t_{eff} - t), \tag{4}$$

so that it depends on dispersion in the beamsplitter and in the sample, and on the difference of their thicknesses. Thus knowledge of the dispersion and the thicknesses enable us to determine the distance $L(\lambda_{eq})$ as a function of the measured equalization wavelength λ_{eq}, and the sensitivity of the displacement measurements

$$S(\lambda_{eq}) = -\frac{dN(\lambda_{eq})}{d\lambda_{eq}}(t_{eff} - t). \tag{5}$$

The estimate of the maximum working distance is $L_{max} \approx |L(\lambda_{min})|$ where λ_{min} is the shortest resolved equalization wavelength.

3.2. Tandem configuration of a non-dispersive Michelson interferometer and a two-mode optical fibre

Previous experimental analyses [13] of spectral interference at the output of a tandem configuration of a non-dispersive Michelson interferometer and a two -mode optical fibre revealed that when a low-resolution spectrometer is employed, only two different spectral interference fringes affected by the intermodal dispersion in the optical fibre can be resolved. The first ones are resolved only in the vicinity of the fibre equalization wavelength λ_{eq} at which the intermodal group OPD $\Delta^g_{10}(z;\lambda_{eq})$ is zero. The second ones are resolved only in the vicinity of the overall equalization wavelength λ_{eqo} at which the positive or the negative OPD in the non-dispersive interferometer becomes equal to the intermodal group OPD. Thus the change of the overall equalization wavelength with the OPD in the interferometer can be used to measure the distance $L = \Delta^g_{10}(z;\lambda_{eqo})/2$ and the displacement with the sensitivity

$$S(\lambda_{eqo}) = \frac{1}{2}\frac{d\Delta^g_{10}(z;\lambda_{eqo})}{d\lambda_{eqo}}. \tag{6}$$

The estimate of the maximum working distance is $L_{max} \approx |\Delta^g_{10}(z;\lambda_{min})/2$, where λ_{min} is the shortest resolved equalization wavelength.

4. Experimental

The experimental set-up used in the application of two new white-light spectral interferometric techniques to measure the distances or displacements in a dispersive or a non-dispersive interferometer is shown in Fig. 1. It consists of a white-light source, a 20 W quartz tungsten halogen lamp, an aperture with a collimating lens, a bulk-optic Michelson interferometer with a beamsplitter and a sample (also in a function of a compensator), a micropositioner connected to one of the mirrors, a microscope objective, micropositioners, a detecting or two-mode optical fibre, a miniature fibre-optic spectrometer S2000, an A/D converter and a personal computer. The beamsplitter and the sample are made of fused silica and have a thickness of 1 cm. The fibre-optic spectrometer S2000 (Ocean Optics, Inc.) of an asymmetric crossed Czerny–Turner design with the input and output focal lengths of 42 and 68 mm, respectively, has a spectral operation range from 350 to 1000 nm and includes a diffraction grating with 600 lines per millimetre, a 2048-element linear CCD-array detector with a Schott glass long-pass filter, a collection lens and a read optical fibre. The wavelength of the spectrometer is calibrated so that a third-order polynomial relation between pixel number and wavelength is used. The spectrometer resolution is in our case given by the effective width of the light beam from a core of the read optical fibre. We used the read optical fibre of a 50 μm core diameter to which a Gaussian response function with the FWHM of 2.0 nm corresponds.

5. Results and discussion

First, we measured the equalization wavelength λ_{eq} as a function of the distance L in the dispersive Michelson interferometer not including the sample. The actual distance is the displacement of mirror 2 from the balanced interferometer configuration with the highest visibility of spatial interference fringes [12]. We displaced mirror 2 by using the micropositioner with a constant step of 10 μm and from the recorded spectral interferograms we revealed that the equalization wavelengths were resolved in the spectral range approximately from 487 to 872 nm and that the corresponding distances varied from −360 to 20 μm. As an example, Fig. 2 shows

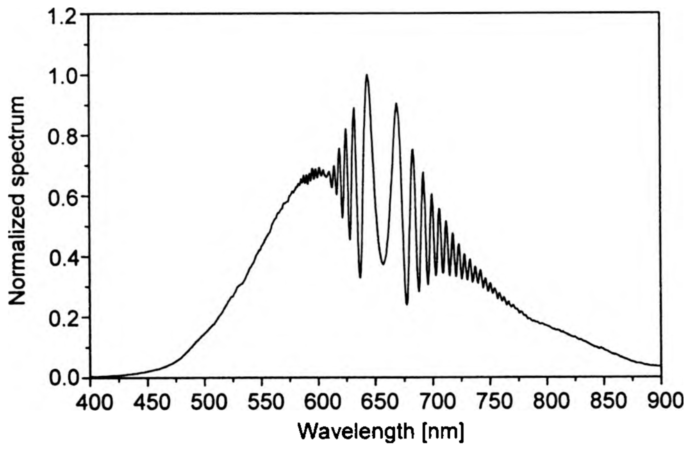

Fig. 2. Example of the spectral interferogram recorded for the distance of −100 μm (the corresponding equalization wavelength is 657.06 nm).

the spectral interferogram recorded for the distance of -100 μm. Figure 2 clearly demonstrates not only the effect of the limited resolving power of the spectrometer on the visibility of the spectral interference fringes, but also an easy evaluation of the equalization wavelength having a value of 657.05 nm.

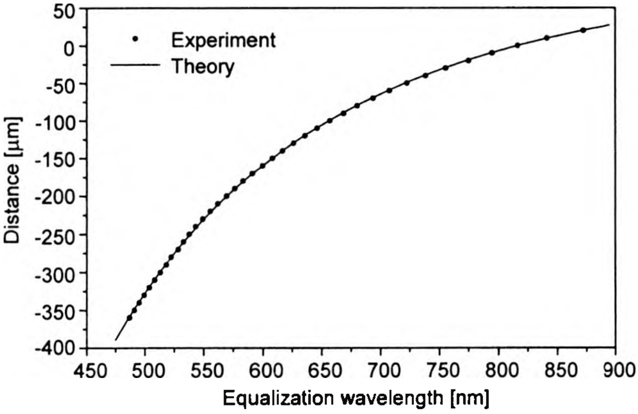

Fig. 3. Distance in the dispersive interferometer (without the sample) as a function of the equalization wavelength (solid curve is the theoretical fit).

Figure 3 then shows the distance L in the Michelson interferometer as a function of the equalization wavelength λ_{eq}. The same figure shows also the theoretical dependence utilizing the fact that we know dispersion in the fused-silica beamsplitter and its effective thickness. The dispersion in the fused-silica beamsplitter is given by the Sellmeier dispersion equation [15] and the beamsplitter effective thickness is evaluated from the slope of the linear dependence of the distance in the Michelson interferometer on the group refractive index of the fused silica determined at given equalization wavelengths (see Eq. (4)). The slope of the corresponding linear fit gives the effective thickness t_{eff} of the beamsplitter of 14 013 μm with a standard

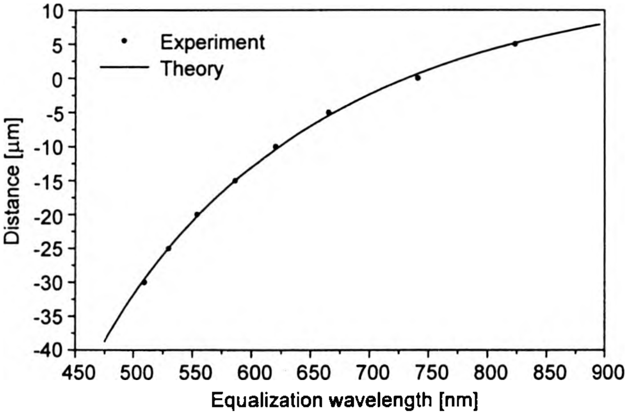

Fig. 4. The same as in Fig. 3, but with the sample.

deviation of 21 μm. Equation (5) then gives for the sensitivity of the displacement measurements 2.4 $\mu m\, nm^{-1}$ at $\lambda_{eq} = 487$ nm or 0.32 $\mu m\, nm^{-1}$ at $\lambda_{eq} =$ 872 nm.

Next we measured the equalization wavelength λ_{eq} as a function of the distance L in the dispersive Michelson interferometer including the sample. We revealed from the recorded spectral interferograms that the equalization wavelengths were resolved in the spectral range approximately from 509 to 823 nm and that the corresponding distances varied from −30 to 5 μm. Figure 4 then shows the distance L in the dispersive Michelson interferometer as a function of the equalization wavelength λ_{eq}. The same figure shows also the theoretical dependence when the difference of thicknesses $t_{eff} - t$ of 1569 μm is obtained with a standard deviation of 21 μm. The sensitivity of the displacement measurements is 0.24 $\mu m\, nm^{-1}$ at $\lambda_{eq} = 509$ nm or 0.045 $\mu m\, nm^{-1}$ at $\lambda_{eq} = 823$ nm.

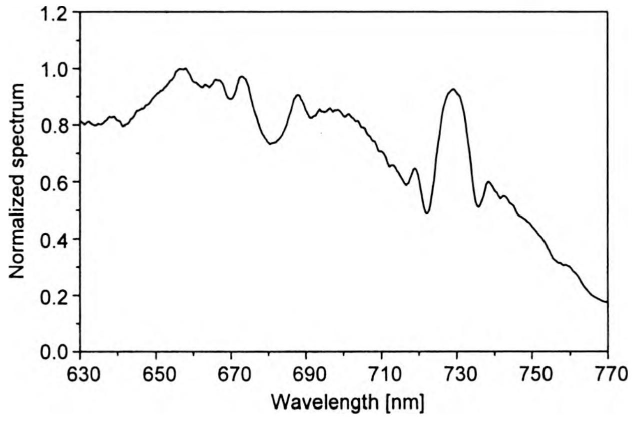

Fig. 5. Example of the spectral interferogram recorded for the distance of 238 μm (the corresponding equalization wavelengths are 681.06 and 729.01 nm).

Second, we used the technique of white-light spectral interferometry with the equalization wavelength determination to measure the distance L in the non -dispersive Michelson interferometer, which is in a tandem configuration with a two-mode optical fibre. First, we used a standard telecommunication, step-index optical fibre of length $z = 2$ m, having a cut-off wavelength of 950 nm and a core diameter of 8 μm. We revealed from the recorded spectral interferograms that the overall equalization wavelengths could be resolved in the spectral range approximately from 667 to 719 nm when the distance in the interferometer varied from 288 to 58 μm with a step of 10 μm. As an example, Fig. 5 shows the spectrum recorded at the output of the two-mode optical fibre when the distance of 238 μm with a precision of 1 μm was adjusted in the interferometer. We can clearly resolve observable spectral interference fringes in two spectral regions. The first ones are in the vicinity of the overall equalization wavelength λ_{eq0} of 681.06 nm and the second ones are in the vicinity of the fibre equalization wavelength λ_{eq} of 729.01 nm. Figure 6 thus

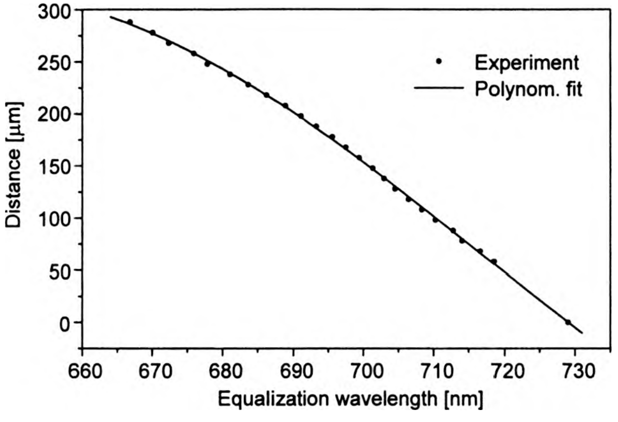

Fig. 6. Distance between the two arms of the compensated interferometer as a function of the equalization wavelength when the first optical fibre is used (solid line is third-order polynomial fit).

shows the distance between the interferometer arms as a function of the overall equalization wavelength together with the zero distance corresponding to the fibre equalization wavelength. In the same figure there is also shown a third-order polynomial fit. Equation (6) then gives for the sensitivity of the displacement measurements $-2.5\ \mu m\ nm^{-1}$ at $\lambda_{eqo} = 667$ nm or $-5.4\ \mu m\ nm^{-1}$ at $\lambda_{eqo} = 719$ nm.

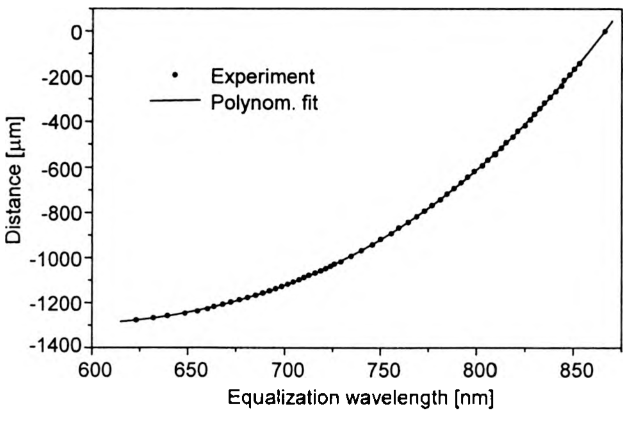

Fig. 7. Distance in the compensated interferometer as a function of the equalization wavelength when the second optical fibre is used (solid line is third-order polynomial fit).

Finally, we used a different step-index optical fibre of length $z = 3.94$ m [13], having a cut-off wavelength of 950 nm and a core diameter of 6 μm. We revealed from the recorded spectral interferograms that the overall equalization wavelengths could be resolved in the spectral range approximately from 623 to 853 nm when the OPD in the interferometer varied from -1277 to -142 μm with a step of 10 or 25 μm. Moreover the fibre equalization wavelength of 866.16 nm was determined. Figure 7 thus shows the distance between the interferometer arms as a function of the overall equalization wavelength together with the zero distance corresponding to the fibre equalization wavelength. In the same figure there is also shown a third -order polynomial fit. The sensitivity of the displacement measurements is 0.95 μm nm^{-1} at $\lambda_{eqo} = 623$ nm or 10.4 μm nm^{-1} at $\lambda_{eqo} = 853$ nm.

6. Conclusions

We proposed two new white-light interferometric techniques employing a low -resolution spectrometer in the equalization wavelength determination to measure distances and displacements. These techniques, which need no phase retrieval procedures to be applied and which work in substantially larger range of distances than conventional white-light interferometric techniques, use a dispersive Michelson interferometer alone or a tandem configuration of a non-dispersive Michelson interferometer and a two-mode optical fibre when the dispersion in the interferometer and the intermodal dispersion in the optical fibre are known. We have demonstrated experimentally that both the dispersion in the interferometer and the intermodal dispersion in the optical fibre affect the range of the measurable distances and the sensitivity of the displacement measurements.

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