Folded Jamin interferometer: a stable instrument for refractive-index measurements

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A novel two-beam interferometer for the measurement of a refractive index or its induced changes is described. This interferometer consists of only two optical elements and is largely insensitive to their movement. A laboratory prototype has been built. It uses a polarized version of the folded Jamin interferometer to allow for convenient phase adjustment. © 1996 Optical Society of America

Simple two-beam interferometers divide an incident laser beam into two beams, which later are joined to yield two output beams whose respective intensities are sinusoidal functions of the optical path difference of the two beams. Typical examples are the Jamin,[1] Mach–Zehnder,[2,3] and Michelson[4] interferometers. All these instruments have two input and two output ports. However, in the case of the Michelson interferometer input and output ports are collocated. The optical path is the sum of the integral of the refractive index over the geometric path and of incidental phase shifts on reflection multiplied by the wavelength. Therefore the output intensities change both because of changes in the relative geometrical path length (this effect is commonly used for high-resolution displacement measurements[5,6]) and because of changes in the relative refractive index between the two paths. This effect can be utilized for the measurement of changes in the refractive index (both real and imaginary parts) in a two-beam interferometer with known geometric path difference.[3,7–11] Just as environmental changes in the refractive index disturb displacement measurements, changes in the geometrical path difference owing to vibration, thermal expansion, etc. disturb measurements of the change in refractive indices. Whereas environmental changes in the refractive index can often be eliminated by evacuation or numerical corrections,[6] changes in the geometrical path difference have been reduced only by careful mechanical design resulting in vibration isolation, temperature stabilization, etc. We discuss a simple interferometer that virtually eliminates changes in the geometrical path difference. A related interferometer, which reduces changes in the geometrical path difference, was described previously.[12]

Considering the three basic two-beam interferometers mentioned above, one notes that the geometric path difference of the Michelson interferometer is independent of rotation of a retroreflector around its vertex. (This is exactly true only for hollow-cube retroreflectors.[5]) However, it is highly sensitive to linear motion of either retroreflector in the beam direction. Exactly the opposite is true for the Jamin interferometer. Linear motion of either of the two optical elements does not affect the output intensities, as both beam paths are changed in exactly the same way, whereas rotation introduces a differential change in path length, leading to a change in the geometric path difference.

The folded Jamin interferometer (Fig. 1) combines both insensitivity to rotation and translation of its two optical elements to result in a simple and virtually vibration-insensitive interferometer. An incoming laser beam is split by a partial beam-splitter coating on the first surface of a plane-parallel plate of thickness t_p. One of the resulting beams is reflected by a partial high-reflectance coating on the second surface. With an appropriate beam-splitter coating, two parallel beams of equal intensity are generated. They are separated by a distance d_p, with

$$d_p = \frac{t_p \sin(2\alpha)}{[(n_p/n_a)^2 - \sin^2 \alpha]^{1/2}}, \tag{1}$$

where α is the angle of incidence and n_a and n_p are the refractive indices of the surrounding medium (air) and of the plate, respectively. A retroreflector is placed in the path of the two parallel beams with its vertex shifted by a distance Δ from their geometrical center (Fig. 1). On retroreflection the beams are displaced by

$$d = d_p \pm d_{ap} = d_p \pm 2\Delta, \tag{2}$$

respectively, where $d_{ap} = 2\Delta$ is the resulting distance between the antiparallel beams. The retroreflected beams recombine on the beam-splitter coating

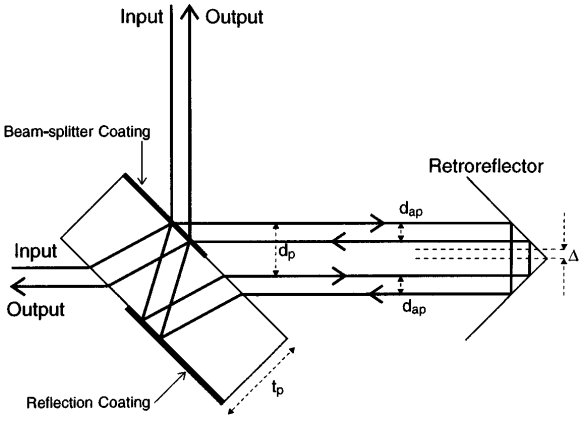

Fig. 1. Folded Jamin interferometer.

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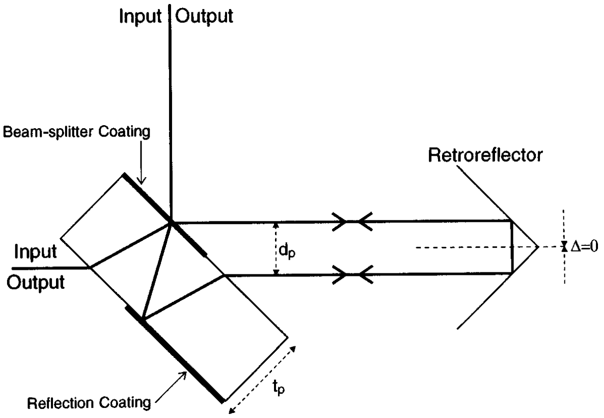

Fig. 2. Folded Jamin interferometer operated as a Sagnac interferometer.

to produce the two interferometer output beams, one antiparallel to the input and the other exiting through the other plate surface. The two beams in the interferometer pass through the same distance in each of the optical elements and in the space between them, resulting in essentially zero path difference (achromatic; i.e., infinite free spectral range) for the empty (constant refractive index in each of the three regions) interferometer, independently of small linear or angular movements of the two elements and independently of wavelength and the dispersion properties of the respective materials. As indicated in Fig. 1, the folded Jamin interferometer has a total of four ports, i.e., two separate input and two separate output ports. Any of these ports may be used as either an input or an output port.

To measure a refractive index, only one input and the corresponding two output ports are used. The material of interest is introduced into one of the beams in the interferometer (or into the two counterpropagating sections of one beam), and length or density of the material is varied. The resulting phase shift can be deduced from the change in the two output signals, yielding the change in refractive index. The second input port can conveniently be used for a pump beam if induced index changes are of interest[8–11] and if a polarizing or dichroic beam-splitter coating is used.

If the offset Δ of the retroreflector position is set to $\Delta = 0$ (Fig. 2), input and output ports become collocated, and the folded Jamin interferometer becomes a Sagnac interferometer.[13–15] In this case, noise that is due to different refractive-index fluctuations in the two beam paths is eliminated, as is the opportunity to measure differences in the refractive index between the two paths.

To manufacture the instrument it might seem advantageous to forgo the plane-parallel beam-splitter plate, which requires custom, partial coatings, in favor of a beam-splitter cube cemented together with a right-angle prism (Fig. 3). Although this alternative can be manufactured much more easily, tolerances for beam parallelism become much larger because of the cement layers, both in the beam-splitter cube and as used to attach the right-angle prism. It seems difficult to achieve beam parallelism of better than 1 arcmin, even on custom basis.

For the second optical element, the retroreflector, either a Porro prism (i.e., a one-dimensional retroreflector) or a corner cube (i.e., a two-dimensional retroreflector) can be used. The trade-off is between angular and linear alignment. In addition, if polarized light is used the relative phase shifts for the different polarizations have to be considered.[16]

The strength of the folded Jamin interferometer, its insensitivity to vibration, is also the source of an apparent weakness: One cannot adjust its phase by moving one of its optical elements by a fraction of a wavelength. Instead, one might be inclined to introduce a transparent object of variable refractive index or length into one of the beams in the interferometer. This solution does not seem practical and in addition may destroy the achromatic character of the interferometer. If phase adjustment is needed, for example, to operate the interferometer in quadrature, it is preferable to use its polarized version.

The polarized, folded Jamin interferometer, shown in Fig. 4, uses an input beam that contains equal power in s and p polarizations (linear polarized at 45°, circular polarized, etc.). The s and p polarizations are separated into the individual beams by a polarizing thin-film coating on the plane-parallel plate, resulting, after an additional reflection of the p-polarized beam, in two parallel, orthogonally polarized beams. A Porro prism is used as retroreflector, as it does not change the polarization of either the s- or the p-polarized beam, though it does introduce a constant phase shift between

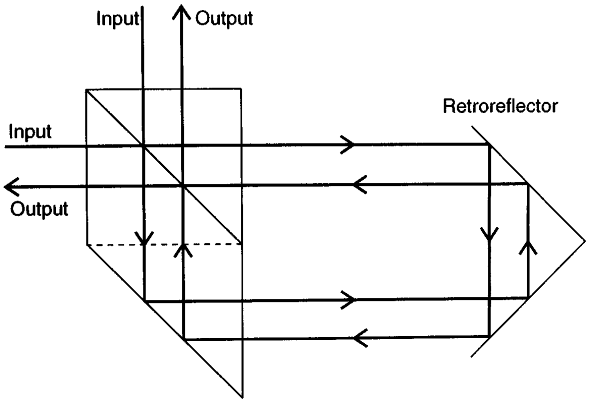

Fig. 3. Beam-splitter cube cemented together with a right-angle prism used as a beam splitter for the folded Jamin interferometer.

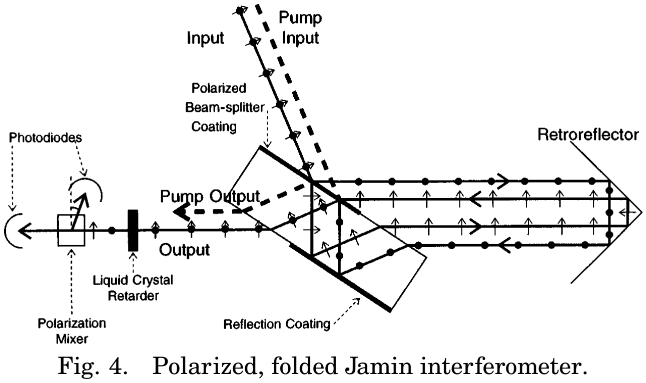

Fig. 4. Polarized, folded Jamin interferometer.

them.[16] After retroreflection the two beams are reunited on the beam-splitter element, resulting in only one output beam. At this point no interference has occurred because of the orthogonal polarizations in the output beam. Finally, a polarization mixer, e.g., a polarized beam-splitter cube rotated by 45° relative to the interferometer plane, mixes s and p polarizations, yielding the two interferometer outputs. One can easily adjust the phase of this polarized interferometer by placing a variable retarder into one of the beam sections where s and p polarizations overlap, i.e., either between the laser and the beam-splitter plate or between the beam-splitter plate and the polarization mixer. For increased convenience and fully automated operation an electrically controlled variable retarder, a liquid-crystal retarder, is used. For higher-frequency operation this retarder can be replaced by a Pockels cell. This setup results in a stable interferometer for the measurement of refractive-index changes with convenient adjustment of the output phase.

The thin-film polarized beam-splitter coating used achieves a polarization ratio of ~40:1 for the predominantly s-polarized, reflected beam and of better than 500:1 for the transmitted p-polarized beam after the angle of incidence has beam optimized near 56°. After the second reflection (transmission) by (through) the coating these values are squared, resulting in good polarization purity.

In our laboratory the polarized, folded Jamin interferometer is used to probe the refractive-index change induced by the absorption of a pump beam. This technique is useful for the measurement of weak and especially broadband absorption,[8,9] such as the light absorption that is due to atmospheric aerosols, which is the topic of our research.[17] In contrast, FM spectroscopy can be used only to measure spectrally narrow absorption.[18] To measure induced index changes, a p-polarized pump beam with a longer wavelength than that of the probe laser is used. This beam is transmitted through the polarized beam-splitter coating and overlaps the counterpropagating s-polarized probe beam (Fig. 4). On the second incidence upon the beam-splitter coating the pump beam is separated from the probe beam and exits parallel to the probe output. Here the pump beam is terminated with a beam stop, and any residual contamination of the probe beam can be removed with an interference filter. As the pump beam overlaps the probe beam in only one of the interferometer arms on absorption, it selectively heats the air in this arm, causing a change in refractive index, which results in a phase shift for the probe beam. This phase shift can be sensitively detected in the difference signal from the photodiodes, especially if the pump beam power is sinusoidally modulated and phase-sensitive detection is employed. Instead of, or in addition to, the p-polarized pump beam, an s-polarized pump beam with a wavelength shorter than the probe laser could be employed. Another option is to use closely spaced pump and probe laser wavelengths and to modulate the pump laser polarization instead of its power. This would cause the pump laser to traverse either interferometer arm alternately, effectively doubling the signal compared with power modulation.

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