HIGH ACCURACY MEASUREMENT OF AIR REFRACTIVE INDEX IN REAL-TIME

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Introduction

With the development of new technologies in semiconductor, aerospace and other industries requiring high resolution in dynamic environments, comes the need for higher measurement accuracy. Typically, a laser interferometer is used to meet these precision measurement requirements. Changes of air refractive index seriously affect accuracy in the measurement environment. With such systems, wavelength compensation for interferometer systems has become important.

There are many compensation methods, such as, Weather Station[1], Wavelength Tracker[2], etc. None of them can accurately compensate for changes in temperature, pressure, humidity and composition in the measuring environment. In order to bridge this gap, Excel Precision Co. designed and developed the REFRACTOMETER[3] (figure 1) to compensate for the effects of environmental changes.

Refractometer is used to determine in real-time absolute index of refraction of air within the measuring environment. The sealed vacuum cavity of Refractometer requires no re-pumping between measurements and allows Refractometer to function well in industrial applications. The Refractometer was designed for large-quantity production without loss of operating accuracy.

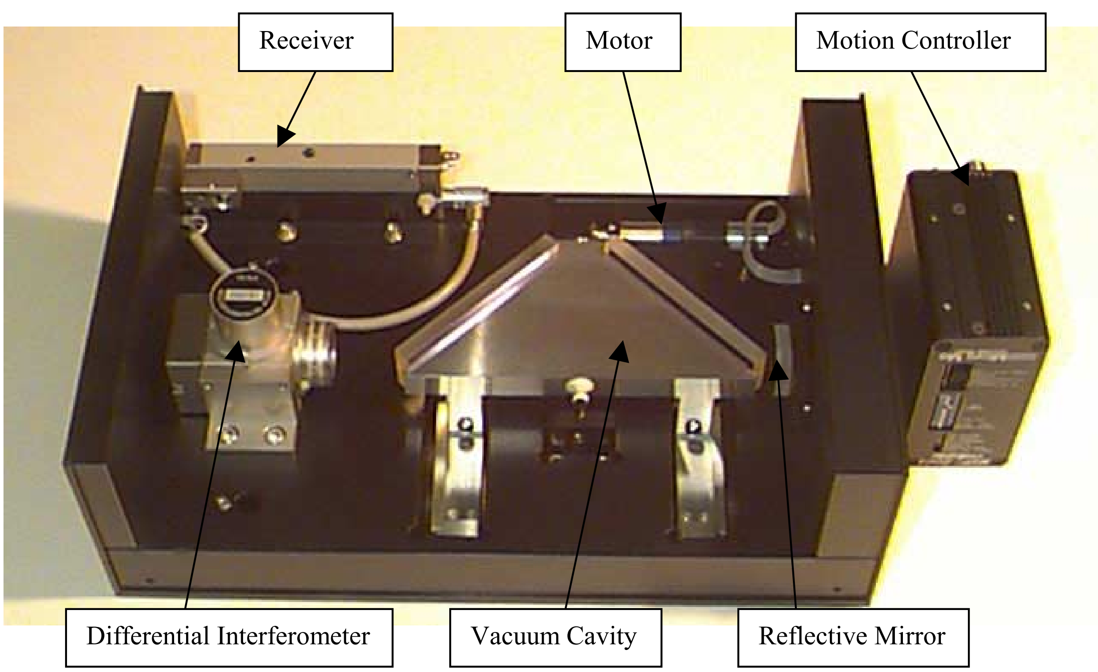

Figure 1. Refractometer

Principle of the measurement

When the laser interferometer performs measurement in air, the laser wavelength is shortened by a factor of n.

$$\lambda_{air} = \frac{\lambda_v}{n} \qquad (1)$$

Where, n is air refractive index

λ_v is laser wavelength in vacuum

λ_{air} is laser wavelength in air

Measurement accuracy is improved by the refractometer by measuring the index of refraction of air and generating a correction factor that is applied to the original measurement data.

Refractometer measures the instantaneous index of refraction of air and provides compensation factor to the laser interferometer system. Measurement of instantaneous index of refraction is achieved by comparing two laser optical paths, one passing through a vacuum and the other through the measuring environment, from a differential interferometer to a reflective mirror, and back to a receiver. The vacuum optical path length is varied by moving a trapezoidal vacuum cavity through a known distance.

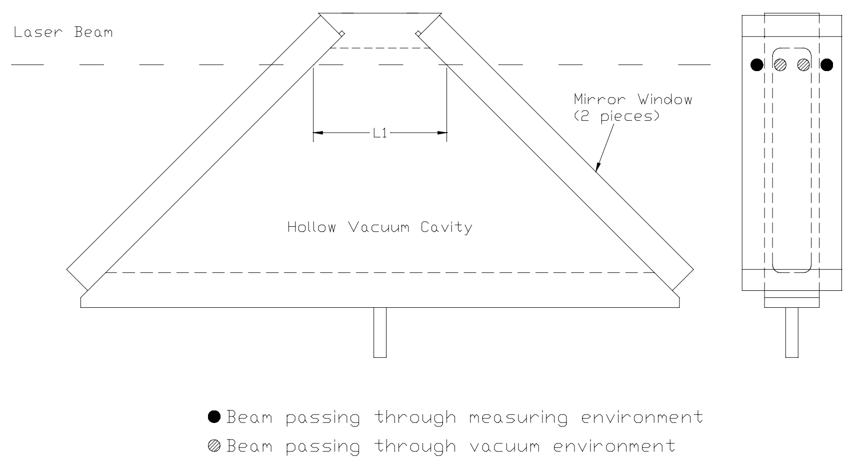

Figure 2. Laser beam goes through short path position

When laser beam goes through short path position (figure 2):

$$(n-1)\cdot L_1 = N_1 \cdot \frac{\lambda_v}{128} \qquad (2)$$

When laser beam goes through long path position (figure 3):

$$(n-1)\cdot L_2 = N_2 \cdot \frac{\lambda_v}{128} \qquad (3)$$

Eq. (3) subtracts Eq. (2), obtains:

$$(n-1)\cdot (L_2 - L_1) = (N_2 - N_1)\cdot \frac{\lambda_v}{128} \qquad (4)$$

Let $N_2 - N_1 = \Delta N$, Eq. (4) becomes:

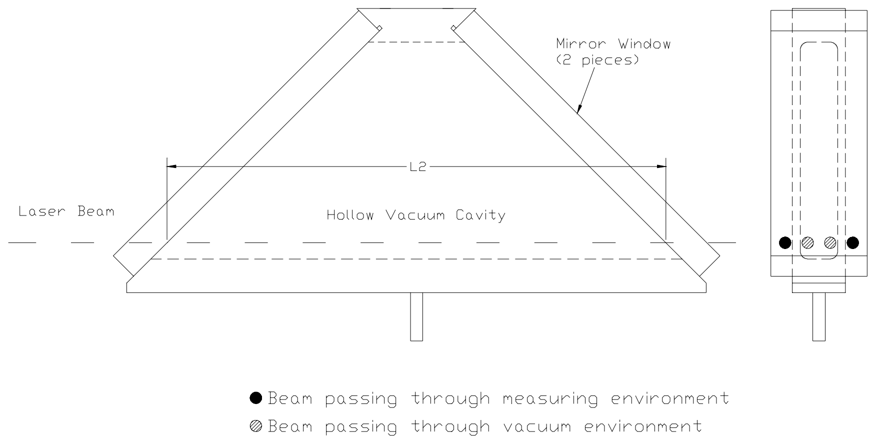

Figure 3. Laser beam goes through long path position

$$(n-1)\cdot(L_2-L_1)=\Delta N\cdot\frac{\lambda_v}{128} \qquad (5)$$

Where,

n is air refractive index in measuring environment
ΔN is differential laser counts between short path position and long path position
L_2 is the physical beam path length at long path position in vacuum cavity
L_1 is the physical beam path length at short path position in vacuum cavity

L_2 and L_1 can be obtained exactly through precise calibration.

During field initialization of the refractometer, application software is used to drive the motor in order to move the vacuum cavity to the short path position, then back to long path position.

Initial ΔN(0) is obtained from computer based signal processing card. So initial n(0) is obtained from Eq. (5).

$$n(0)=1+\frac{\Delta N(0)\cdot\lambda_v}{128\cdot(L_2-L_1)} \qquad (6)$$

While vacuum cavity stays at long path position, change of air refractive index can get from Eq. (3):

$$dn=\frac{\lambda_v}{128\cdot L_2}\cdot dN_2 \qquad (7)$$

$dN_2=d(\Delta N)$, So

$$n(t)=n(0)+\Delta n=n(0)+\frac{\lambda_v}{128\cdot L_2}\cdot\left[\Delta N(t)-\Delta N(0)\right] \qquad (8)$$

Eq. (8) is used for continuous measurement for air refractive index.

Experiments

2 units of refractometer were compared with a standard unit of refractometer in the measuring environment. The standard refractometer was the same as normal refractometer, except that its

vacuum cavity is connected to a vacuum pump. This standard unit was maintained at a high vacuum level during the comparison testing. Comparison results were shown in table 1 & 2.

Table 1. Comparison results between standard unit and unit 1

Test S/N	Air refractive index for standard unit	Air refractive index for unit 1	Difference between standard unit & unit 1
1	1.000266140	1.000266101	3.9×10^{-8}
2	1.000266113	1.000266101	1.2×10^{-8}
3	1.000266214	1.000266177	3.7×10^{-8}
4	1.000268868	1.000268902	-3.4×10^{-8}
5	1.000267679	1.000267636	4.3×10^{-8}
6	1.000271249	1.000271209	4.0×10^{-8}
7	1.000265083	1.000265038	4.5×10^{-8}
8	1.000268409	1.000268454	-4.5×10^{-8}
9	1.000269081	1.000269092	-1.1×10^{-8}
10	1.000268905	1.000268864	4.1×10^{-8}
11	1.000268830	1.000268864	-3.4×10^{-8}

Table 2. Comparison results between standard unit and unit 2

Test S/N	Air refractive index for standard unit	Air refractive index for unit 2	Difference between standard unit & unit 2
1	1.000267078	1.000267083	-5.0×10^{-9}
2	1.000266473	1.000266445	2.8×10^{-8}
3	1.000265275	1.000265302	-2.7×10^{-8}
4	1.000266862	1.000266845	1.7×10^{-8}
5	1.000266501	1.000266513	-1.2×10^{-8}
6	1.000266492	1.000266513	-2.1×10^{-8}
7	1.000265755	1.000265769	-1.4×10^{-8}
8	1.000265753	1.000265769	-1.6×10^{-8}
9	1.000265657	1.000265695	-3.8×10^{-8}
10	1.000265892	1.000265849	4.3×10^{-8}
11	1.000265716	1.000265759	-4.3×10^{-8}

From comparison results (Table 1 &2), the accuracy of refractometer is better than $\pm 5.0 \times 10^{-8}$.

Conclusion

We have designed and developed the high accuracy refractometer for the measurement of absolute air refractive index in real-time. Attractive features of this approach are no re-pumping requirement, high accuracy, high repeatability, real-time measurement and real-time compensation. It is easy to set up and align. One typical application would be for correcting displacement measurements of an X-Y stage with laser interferometer.

Reference

1. John C. Tsai, Mervyn I. Hopson, “Environment parameter measurement device and method for laser interferometry”, United States Patent Number: 5920392.
2. Scott M. Detro, Alan H. Field, “Wavelength tracking compensator for an interferometer”, United States Patent Number: 4765741.
3. John C. Tsai, “Ambient air refracture index measuring device”, United States Patent Number: 5394244.