"Method of Refractometry and Refractometer Therefor"

This invention relates to a method of refractometry and a refractometer for use therein, and more particularly to an improved method of measuring the refractive index of a liquid using optical domain reflectometry and to an improved optical domain refractometer.

Many proposals have been made for measuring the refractive index (RI) of a liquid using an optical fibre as the sensing element. Most known methods are based on the leakage of optical power from a suitable fibre sensor immersed in a liquid of unknown RI. By measuring the reduced power output, which depends on the refractive indices of the fibre material and liquid, the RI of the latter is determined. The fibre sensors used in these refractometers are rather complex. In another known method, the sensor is simply an open-ended, square-cut fibre immersed in a liquid of unknown RI, but optical frequency domain reflectometry (OFDR) is used to process the signal reflected at the glass/liquid interface.

The accuracy of the refractometers described above clearly depends on the stability of the electro-optical transmitters and opto-electronic receivers employed. The main cause of instability of these instruments is ambient temperature fluctuation.

A principal object of the present invention is to provide an improved optical domain reflectometry technique and an improved refractometer for carrying out the same.

In accordance with one aspect of the present invention there is

provided a method of measuring the refractive index of a liquid by optical frequency domain reflectometry, comprising changing the frequency of modulation of the output intensity of the light source, measuring the received optical power before and after the change in modulation frequency and obtaining a measure of the refractive index by dividing one of the measurements by the other.

By the use of this method measurement drifts due to alterations of ambient conditions, such as temperature fluctuations, will be minimised.

Preferably, the intensity of the output of superluminescent laser diode is modulated by a sinusoidal signal, and microprocessor means is utilised to control the frequency of modulation of the diode output and to take readings before and after such change of frequency and display a read out resulting from a division of said readings. The sensor means employed is preferably a square-cut optical fibre immersed in the liquid to be measured, said sensor means being connected to the light source via an optical directional coupler in turn connected to an optical receiver, the receiver in turn being connected to the microprocessor via programmable bandpass filter and averager.

In a preferred embodiment of the invention the sensor is a square-cut, open-ended fibre 1 km long and the modulation frequency is varied between 72 kHz and 124kHz.

In accordance with another aspect of the present invention there is provided a refractometer for carrying out the method defined in the four immediately preceding paragraphs, the refractometer comprising a light source preferably with means for intensity modulation, an optical fibre sensor for immersion in a liquid to be measured, a directional coupler between the light source and sensor, an optical receiver connected to the directional coupler, means for varying the modulation frequency output characteristic of the light source and means for comparing the input to the receiver before and after varying the light source output characteristic thereby to obtain a measure of refractive index.

Said comparison means preferably comprises a programmable bandpass filter and averager connected to the microprocessor means, the latter being adapted to vary the output characteristic of the light source and to provide a read-out computed by comparing inputs to the receiver before and after variation of the light source output.

Preferably the light source is a superluminescent laser diode and sinusoidal signal means is provided for modulating the light output of the diode. Preferably the sinusoidal signal means is controlled by the microprocessor means.

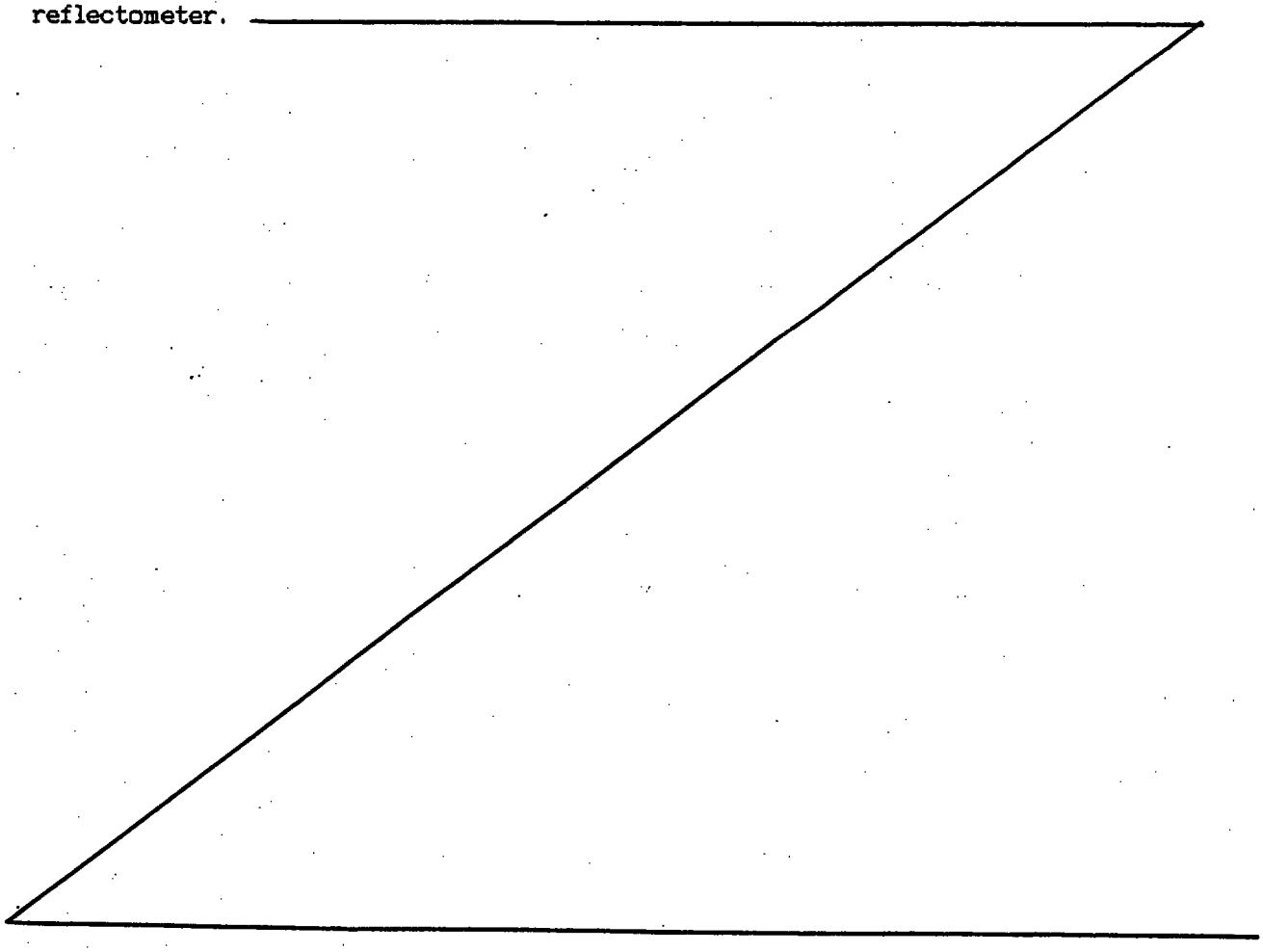
A preferred embodiment of the invention will now be described with reference to the accompanying diagrammatic drawings, in which:

Figure 1 is a block diagram of a refractometer in accordance with the invention,

Figure 2 is a calibration curve obtained using the refractometer of Figure 1,

Figure 3 is a graph of measurements made using the refractometer of Figure 1 at one minute intervals over a one hour period, and

Figure 4 is a graph of measurements made at the same intervals and over the same period as in Figure 3 but using a known optical frequency domain reflectometer.



The block diagram of the refractometer is shown in Fig. 1. An electrical signal

$$E_{tx}(t) = A \cos(\omega t + \theta_o) \qquad (1)$$

intensity modulates the laser diode optical source. Here, the amplitude A is constant and the frequency ω, controlled by the microprocessor, can take on one of two discrete values ω_1 or ω_2.

The light power launched from the source has an a.c. component (at ω_1 or ω_2) with a phasor representation

$$P_{tx} = c_{tx} A e^{j\theta_o} \qquad (2)$$

where c_{tx} is the constant of proportionality relating the electrical input voltage to the a.c. component of the power launched from the source and θ_o is an initial phase angle. Clearly, as the environmental conditions change, so too will c_{tx}, the main cause of this drift being temperature fluctuations affecting the stability of the source output power.

The light power reflected back at the glass/liquid interface and subsequently channelled into the receiver, has an a.c. component

$$P_{rf} = R(n_f, n_1) P_{tx} e^{j\theta_i} \qquad (3)$$

where the phase shift θ_i at frequency ω_i is due to the time delay involved and $R(n_f, n_l)$ represents the overall power loss. This is proportional to

$$\left[\frac{n_f - n_l}{n_f + n_l}\right]^2, \tag{4}$$

the power reflection coefficient at the glass/liquid interface, as derived in [6], for a perfectly square smooth endface. n_f and n_l are the RIs of the fibre core and liquid respectively.

The unavoidable light power at the receiver, due to both leakage through the directional coupler and reflections at optical discontinuities in the system, has an a.c. component

$$P_{lk} = L\, P_{tx}\, e^{j\phi_i} \tag{5}$$

where L represents the power loss and ϕ_i (at ω_i) the phase shift involved.

Clearly the a.c. component of the total received optical power is

$$P_{rx} = P_{rf} + P_{lk} \tag{6}$$

and this gives rise to an electrical voltage at frequency ω_i having a phasor representation

$$E_i = c_{rx} P_{rx} \tag{7}$$

where c_{rx} is the constant of proportionality relating the a.c. components of the optical input power and output voltage at the receiver. Like c_{tx}, c_{rx} will also drift as environmental conditions vary. From (2) - (7), the magnitude of the electrical output from the receiver is

$$M_i = A\, c_{tx}\, c_{rx} \left[L e^{j\phi_i} + R(n_f, n_1)\, e^{j\theta_i} \right] \tag{8}$$

and will change as c_{tx} and c_{rx} drift. However, M_i will depend on the frequency ω_i of the modulating sinusoidal signal, so that instead of using M_i directly to measure the RI of the liquid as in conventional refractometers [1 - 5], the RI of the liquid may now be estimated from

$$\frac{M_2}{M_1} = \left[\frac{L e^{i\phi_2} + R(n_f, n_1)\, e^{j\theta_2}}{L e^{j\phi_1} + R(n_f, n_1)\, e^{j\theta_1}} \right] \tag{9}$$

which is independent of c_{tx} and c_{rx}. Thus, by measuring the magnitude M_1 of the output at input frequency ω_1, followed shortly by a similar measurement at frequency ω_2 to obtain M_2, the problem of drift associated with the electro-optical components may be eliminated, at least in principle. The unknown RI may then be obtained by looking up a calibration curve of M_2/M_1 against RI.

Having described the principle of drift reduction, some experimental results are now presented to demonstrate the improvement in accuracy that results from using this technique. In the experimental refractometer, the length of the fibre is 1 km and the fibre core has an RI of 1.456. To reduce modal noise [7], a superluminescent diode at 1.3 μm is used as the light source. The choice of the frequencies ω_1 and ω_2 are dependent on the fibre length. For the 1km fibre used, ω_1 ad ω_2 are 72 kHz and 124 kHz respectively. These are chosen so that the ratio M_2/M_1 changes most rapidly with the liquid's refractive index. Essentially, choosing ω_1 to be 72 kHz causes the two terms in the denominator of (9) to be in antiphase, whereas with ω_2 equal to 124 kHz, the two terms in the numerator of (9) are in phase.

Fig. 2 shows the calibration curve for the new refractometer. The vertical and horizontal axes give, respectively, the RIs of standard and certified test liquids and the corresponding ratios (9) obtained experimentally. Fig. 3 shows the drift and stability of the new refractometer over an observation period of 1 hour in which measurements are taken every 1 minute. Fig. 4 shows the corresponding results obtained over the same observation interval (and the same experimental setup) by using the conventional method of finding the RI directly from one measurement of the magnitude of the receiver output. A substantial improvement in drift and stability of the measurement is thus attained with the new refractometer.

CLAIMS

1. A method of measuring the refractive index of a liquid by optical frequency domain reflectometry, comprising changing the frequency of modulation of the output intensity of the light source, measuring the received optical power before and after the change in modulation frequency and obtaining a measure of the refractive index by dividing one of the measurements by the other.

2. A method as claimed in Claim 1, wherein the intensity of the output of the superluminescent laser diode is modulated by a sinusoidal signal, and wherein microprocessor means is utilised to control modulation of the diode output and to compare readings before and after such modulation and display a read-out resulting from a division of said readings.

3. A method as claimed in Claim 2, wherein sensor means is employed comprising a square-cut optical fibre immersed in the liquid to be measured, said sensor means being connected to the light source via an optical directional coupler in turn connected to an optical receiver, the receiver in turn being connected to the microprocessor via a programmable bandpass filter and averager.

4. Method as claimed in Claim 3, wherein the sensor is a fibre 1 km long and wherein the output modulation frequency of the diode is varied between 72 kHz and 124 kHz.

5. A refractometer for carrying out the method claimed in any one of the preceding claims, comprising a light source, a means for frequency modulating the output of said source, an optical fibre sensor for immersion in a liquid to be measured, a directional coupler between the light source and sensor, an optical receiver connected to the directional coupler, means for varying the modulation frequency output characteristic of the light source and means for comparing the input to the receiver before and after varying the light source output characteristic to obtain a measure of refractive index.

6. A refractometer as claimed in claim 5, wherein said comparison means comprises a programmable bandpass filter and averager connected to microprocessor means, the latter being adapted to vary the output characteristic of the light source and to provide a read-out computed by comparing inputs to the receiver before and after variation of the light source output.

7. A refractometer as claimed in Claim 5 or Claim 6, wherein the light source is a superluminescent laser diode and wherein sinusoidal signal means is provided for modulating the light output of the diode.

8. A refractometer as claimed in Claim 7 as appendant to Claim 6, wherein the sinusoidal signal means is controlled by the microprocessor means.

9. A method of measuring the refractive index of a liquid as claimed in Claim 1 substantially as herein described.

10. A refractometer for carrying out the method claimed in any one of Claims 1 to 4 and 9 substantially as described in the Description with reference to and as shown in Figure 1 of the accompanying diagrammatic drawings.