Design of multimode tapered fibre sensor for glucose detection

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In this paper the comparison behaviour between a tapered silica Multi-Mode Fibre (MMF) and a Plastic Multi-Mode (PMM) fibre is proposed. The tapered silica MMF (tapered core and cladding) and PMM fibre (only core) sensors use a Tunable Laser Source (TLS) at 1550 nm and a yellow He-Ne laser at 594 nm as the sources for measuring the attenuation of the input signal when the sensor is being soaked into the glucose solution. From this work, the tapered PMM fibre performs better in terms of its linearity, and provides a reliable calibration graph of glucose concentration against output signal. It has a sensitivity of 0.0088 mV/% and an error of 2.6 percent with a resolution of 0.36%. The tapered silica MMF has a better sensitivity, error and a better resolution but a lesser degree of linearity.

(Received January 23, 2013; accepted June 12, 2013)
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Keywords: Tapered fibre probe, Fibre optic sensor, Glucose in deionized water

1. Introduction

The efforts to develop smaller but more sensitive and accurate sensors to cater to a large range of physical, chemical and biomedical measurements constitute a substantial drive for optoelectronics research today. The reason for this is because sensors based on optical fibres possess a number of key advantages over conventional electrical sensors, including being intrinsically safe in chemically hostile or explosive environments (due to the absence of sparks) low susceptibility to electromagnetic interference, electrically passive operation, high sensitivity, light weight and geometrical versatility. These advantages have seen a number of potential applications for optical fibre sensors, such as the detection and measurement of temperature and strain, vibrational measurements and accelerometer calibration as well as bio-chemical measurements such as pH and component concentration [1-6].

The measurement of the optical refractive index of a material is of special interest in the development of optical sensors. Refractometers are frequently used for the identification of various organic and in-organic compounds and fibre optic sensors for measuring the refractive index of liquid have been successfully designed and developed [7-8]. Similarly, non-invasive sensors based on polarimetric methods have also been developed to provide non-invasive measurement of blood sugar levels via the glucose concentration in the aqueous humour of the eye. Efforts by M. Yokota et al. [9] have successfully measured glucose concentration with a resolution of 0.01 g dl^{-1} using a fibre Faraday rotator as a polarization modulator and/or the polarization compensator. The non-invasive measurement of blood glucose levels is an important area of research due to its importance in providing a potential painless alternative for diabetes patients to regulate their blood sugar levels (current methods require a blood sample, causing pain and discomfort as well as increasing the risk of infection due to the need for multiple samples from the same area).

In this paper a comparison of the performance of silica and plastic optical fibres as candidates for the measurement of glucose concentrations are presented. The sensors are immersed in a solution of de-ionised water and glucose at different concentrations and the optical power of the output of the sensors are measured. The performances of the sensors are compared in terms of their sensitivity and error as well as resolution. The linearity of the sensors are also analysed as this will provide an indication of the sensor's performance in actual applications.

2. Experimental setup

The experimental setup consists of a silica Multi-Mode Fibre (MMF) with a core and cladding diameter of 62.5 µm and 125 µm respectively, and a Numerical Aperture (NA) of 0.241 (ThorLabs). The refractive indices of the core and cladding are 1.47 and 1.45 respectively. The acceptance angle is 32^0 with an attenuation of greater than 0.9 dB/km at 1550 nm. Another fibre that is also used in this experiment is a Plastic Multi-Mode Fibre (PMM), from Autonics Corp., Seoul, South Korea. The fibre has a core diameter of 0.735 mm and the overall diameter size of the fibre (including the cladding) is 0.750 mm. It has a core index of refraction of 1.492 and cladding index of refraction of 1.402 with a NA of 0.51, attenuation of 150 – 300 dB/km at 650 nm and an acceptance angle of 61°. The fibre is unjacketed. The testing solution used in this experiment is D (+) - Glucose ($C_6H_{12}O_6$ g/mol) which is obtained from Merck, KGaA Darnstadt, Germany.

The experimental setup consists of two sub-sections; the first is the fabrication of the fibre that will be used in this experiment and the usage of plastic fibres, whilst the second section mainly illustrates the actual experimental technique.

2.1. Fabrication of the fibres

In the following section, the fabrication of the tapered MMF silica fibre is described in detail, followed by the description of the PMM.

2.1.1 Multimode silica fibre

The tapering of the micro-fibre is done by first removing the coating of a standard MMF. This is done by placing the MMF between two fibre holders which are fixed onto two translation stages. A built in burner is used, which is fixed at the centre of the MMF and the fibre is being pulled slowly at both ends so as to reduce the fibre waist diameter to approximately 5.2 µm and a length of 2 cm. This is done by having a constant and optimum pulling speed, and this is shown in Fig. 1 below:

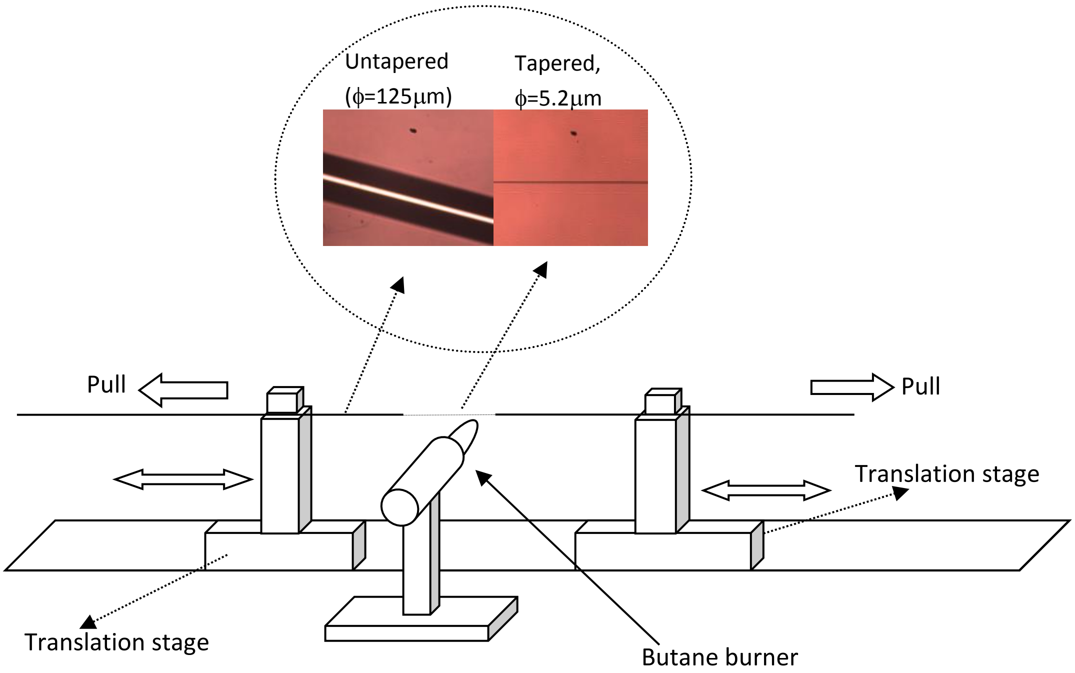


Fig. 1. Schematic diagram of the tapering process of the MMF silica fibre.

As a precautionary step, the flame should be clean and the burning gas flow should be well controlled and steps should be taken to reduce any air convection flow that may cause breakage in the fibre during the drawing process. One of the fibre ends is connected to a Tunable Laser Source (TLS) and the other end is connected to a power meter as to monitor the drop in the output power during the tapering process.

2.1.2. Multimode plastic fibre

The PMM fibre has an outer diameter of 750 µm and a length of 30 cm. The core and cladding of this fibre is made from PMMA and a fluorine polymer (CF_2=$CFOCF_2CF_2CF$=CF_2), respectively. The un-tapered and tapered PMM fibres are shown in Fig. 2 (a) and (b).

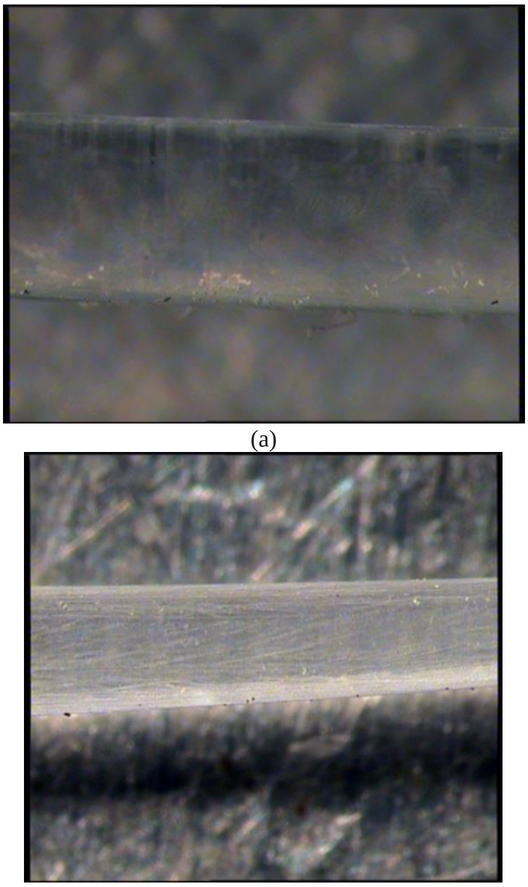


Fig. 2. (a) Un-tapered PMM Fibre (Diameter of 0.75 mm) and (b) Tapered PMM Fibre (Diameter of 0.35 mm).

The fibre is chemically tapered using acetone, distilled water, 2-propanol and sand paper. The acetone solution is applied to the PMM using a cotton bud. The PMM fibre is then neutralized with the distilled water. The milky white surface around the outer cylinder of the plastic fibre is removed by sand paper. This process is repeated until the tapered fibres have a stripped region length of 0.35 cm and a diameter of 0.35 mm. Finally, the tapered PMM fibre is cleaned using the 2-propanol (Isopropyl Alcohol).

2.2 Design of experiment

The experimental setup for sensing different glucose solution concentrations is shown below with the case of a silica MMF fibre in Fig. 3 and Fig. 4 for PMM fibre. In the setup of Fig. 3, the experiment consists of a fibre-optic transmitter in the form of a TLS with a maximum output power of +8 dBm with tunability of 100 nm from 1520 nm to 1620 nm. In this experiment the signal wavelength is fixed at 1550 nm and a sensitive Optical Power Meter (OPM). The tapered fibre (Fibre Optic Probe) is first immersed in de-ionized water as to measure the output power of a 0% glucose concentration. During the experiment, the errors caused by temperature are taken to be negligible [10] and the temperature is kept constant at 25^{o}C.

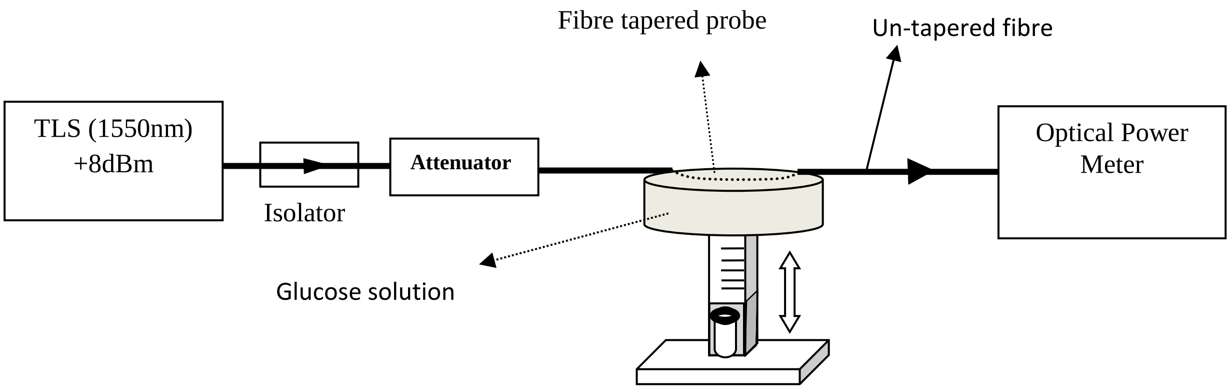


Fig. 3. Experimental setup for using the tapered silica MMF for glucose detection.

The experiment is repeated using the tapered PMM fibre and this is shown in Fig. 4. This figure shows the schematic diagram of the setup of the proposed sensor. Both of these fibre optic sensors are based on the principle of Attenuated Total Internal Reflection (ATR), whereby the cladding of the optical waveguide is reduced and this will expose a sizeable portion of the optical signal into the test solution. Normally, this type of wave is called the evanescent wave and will interact with the solution and will cause attenuation depending on the concentration of the solution.

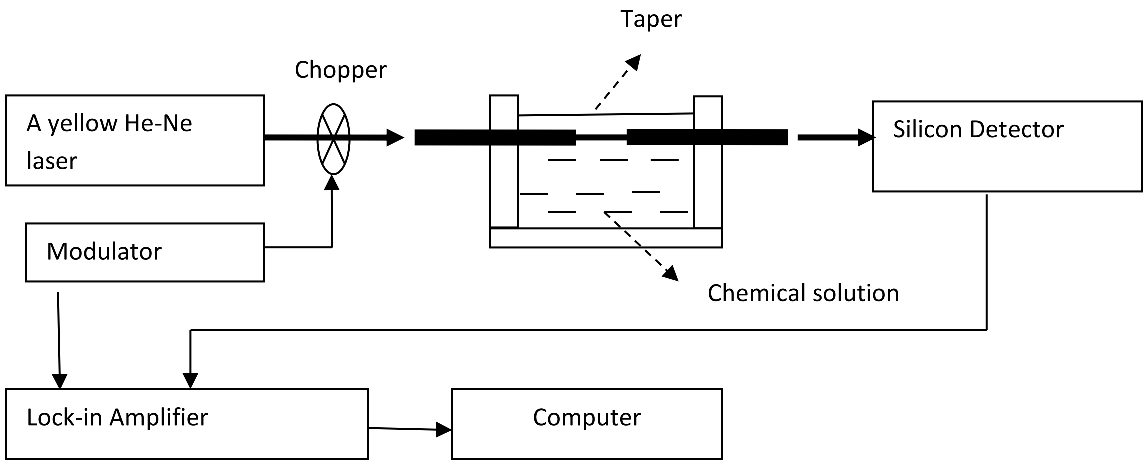


Fig. 4. Experimental setup for using the tapered PMM Fibre for glucose detection.

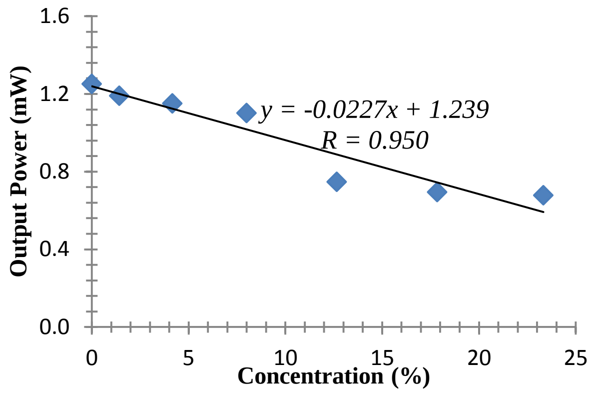
Basically, the exposed core (most of the cladding has been removed) is surrounded by the test solution as to get the maximum interaction between the evanescent wave and the change in the refractive index of the test solution due to the different concentrations. The setup consists of a He-Ne light source, an external mechanical chopper, a highly sensitive photo-detector and a lock-in amplifier. The light source operates at a wavelength of 594 nm with an average output power of 3 mW and having a beam diameter of 0.75 mm as well as a divergence of 0.92 mrads. The light source is set at a modulation frequency of 200 Hz before being launched into the tapered plastic fibre that is placed in a petri dish filled with the test solution. The photo-detector is placed at the other end of the fibre as to convert the received optical signal into an electrical signal that is then fed into a lock-in amplifier together with the output frequency from the mechanical chopper (which acts as the reference signal for the lock-in amplifier). The reference signal from the chopper will match with the input electrical signal from the photo-diode. This will allow a very sensitive detection system that will remove the noises generated by the laser source, photo-detector and the electrical amplifier that is connected to the photo-detector. The light source, the plastic fibre in the petri dish and the detector are aligned in a straight line so as to minimize bending losses that may occur in the plastic fibre, and this will increase the accuracy of the measurement.

3. Results and discussions

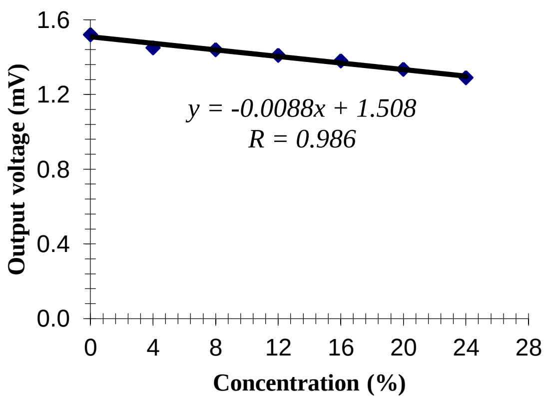
The experimental results taken from these two setups are presented below, with sub-section 3.1 discussing the results from the tapered silica MMF and sub-section 3.2 for the case of the tapered PMM fibre.

3.1. Tapered Silica MMF

The experiment is carried out to study the variation of the transmitted power against the different glucose concentration and this is being presented in Fig. 5 (a) for the case of the tapered silica MMF fibre and (b) for the case of the tapered PMM fibre.



(a)



(b)

Fig. 5. Output Power Variation with Different Glucose Concentrations for (a) Tapered Silica MMF Fibre and (b) Tapered PMM Fibre.

From this measurement, it can be inferred that a glucose concentration as low as 1.4% with the corresponding refractive index of 1.33247 can be detected without any difficulty. Also from the figure, it can be seen that the output power decreases as the glucose concentration increases. For the case of the tapered silica MMF fibre, Table 1 provides the average refractive index against the glucose concentration as calculated from [8] using the equation:

$$n = 0.00012c + 1.3323 \,, \quad (1)$$

whereby n is the refractive index and c is the concentration.

Table 1. Average Refractive Index for Different Glucose Concentrations (%).

Glucose Concentration (%)	**Average Refractive Index**
0	1.3323000
1.43	1.3324714
4.17	1.3328000
8.00	1.3332600
12.66	1.3338190
17.86	1.3344429
23.33	1.3351000

From the regression analysis, the calculated linear correlation coefficient, R is 0.950. The slope of the graph as measured is about 0.0227 mW/% of the glucose solution concentration. The level of confidence in the readings obtained by the system can be determined by the standard deviation of the readings. For each point, approximately 9 measurements are taken and its average value is computed. The maximum standard deviation is about 0.01 mW, taking into account other errors that may take place. In terms of the percentage error, this is about 0.29 percent. The resolution of the sensor, which is the smallest glucose concentration detectable, is determined by dividing the standard deviation with the slope of the sensor, and in this case the resolution that can be achieved using the tapered silica MMF fibre is a about 0.36% of glucose concentration. The summarized values of the above for the tapered silica MMF are given in Table 2.

As can be seen in the graph, the last three points does not indicate good linearity, although using the tapered silica MMF fibre allows for the measurement of lower glucose concentrations. This could be due to, in the case of the tapered silica MMF fibre, the cladding is not removed but rather having a reduced diameter within the neck of the tapered region; thus the ratio between the core and cladding is still retained. As a result of this, a major portion of the effervescent wave still travels within the cladding, and only a small amount will interact with the glucose solution. As a result of this, the change in the refractive index of the glucose solution will only have a small effect onto this effervescent wave. This will not cause significant attenuation onto the multimode wave that propagates in the fibre. This issue needs to be further studied. Besides this issue, the other problem could be that the tapered silica MMF is highly sensitive due to its dimensions that make it very thin and fragile and therefore any external air disturbance will affect the measurement. To overcome this problem, the experiment must be carried out in an enclosed chamber.

3.2. Tapered PMM fibre

The results of the tapered PMM fibre are also shown in the same figure, whereby the measurement of the transmitted optical power against an increasing glucose solution concentration is taken. The slope of the measurement is about 0.0088 mV/% with the glucose concentration being varied from 0 to 24%, as was done with the case of the tapered silica MMF fibre. Although the units may be different, the slopes can provide the necessary information on the functionality of the fibre sensors. As in a similar argument to the case of the tapered silica MMF fibre, the voltage drops as the glucose concentration increases, and the computed maximum standard deviation is 0.04 mV, and the maximum percentage error is about 2.6 per cent (this value is calculated by taking the standard deviation divided by the mean value). The resolution of the tapered PMM fibre sensor is also determined in a similar manner to that of the tapered silica MMF, and in this case the resolution is determined to be a glucose concentration of 4.5%. It can be seen that the linearity of the measurement based on the tapered PMM fibre is superior as compared to the tapered silica MMF fibre, although the steepness of the slope is lesser. The calculated linear correlation coefficient, R is 0.986 that is better than that of the tapered silica MMF fibre and the resolution of measurement of the glucose concentration is comparable to that of the tapered silica MMF fibre. This indicates that the PMM fibre with the exposed core gives a better performance in terms of providing effective interaction of the effervescent wave and the solution that now acts as the cladding. This will give a direct effect onto the effervescent wave and thus providing a more accurate measurement.

Table 2 provides the performance comparison of both methods, namely that of the tapered silica MMF fibre and the tapered PMM fibre.

Table 2. Performance Comparison between the Tapered Silica MMF Fibre and the Tapered PMM Fibre for Glucose Concentration Detection.

Parameter	Value	
	Tapered Silica MMF Fibre	**Tapered plastic fibre**
Sensitivity (mW, mV) / % Glucose Concentration	0.0277 mW/%	0.0088 mV/%
Error in terms of its maximum standard deviation for each point measurement	± 0.01 mW	± 0.04 mV
Error in Terms of Percentage	0.29%	2.6%
Linear Correlation Coefficient, R	More than 95%	More than 98%
Resolution (% concentration of glucose)	0.36%	4.5%
Taper ratio (d_U/d_T) Where: d_U and d_T is untapered and tapered fibre diameter, respectively.	24.04	2.14 (cladding has been removed completely)

From Table 2, it can be inferred that although the tapered silica MMF fibre has a better sensitivity as compared to the tapered PMM fibre, but the linearity and the result consistency is better in the case of the tapered PMM fibre. Although the percentage error of the tapered silica MMF fibre is better than that of the tapered PMM fibre, one needs to stress that the linearity plays an important role in the actual application of this sensor. As shown in the figure, the tapered PMM fibre has all its points fall onto the line, providing a good calibration graph for measuring the glucose percentage. The resolution of the plastic fibre however needs to be further improved by having a smaller core diameter as compared to the one presently being used. Further works is required on the tapered silica MMF fibre to improve the result linearity and a clear understanding is required on how the tapered silica MMF fibre interacts with the glucose solution.

4. Conclusion

In this work we present the development and comparison of two tapered fibres sensors for the measurement of varying glucose concentrations in a solution. The two tapered fibre sensors are fabricated from a silica MMF fibre and a PMM fibre. The tapered silica MMF fibre shows a sensitivity of 0.0277 mW% with an error of 0.29 per cent. The resolution of the tapered silica MMF fibre is about a glucose concentration of 0.36%. In the case of the tapered PMM fibre, it has a sensitivity of 0.0088 mV/% with an error of 2.6 per cent and a resolution of a glucose concentration of 4.5%. Although from these values the tapered silica MMF fibre gives a better sensitivity and resolution, but it does not provide good linearity as that of the tapered PMM fibre. For actual applications, the tapered PMM fibre will fare better because it has a very pronounced linearity for a glucose concentration measurement as shown in this experiment.

Reference

[1] M. Yasin, S. W. Harun, Kusminarto, Karyono, Warsono, A. H. Zaidan, Optoelectron. Adv. Mater. **11**, 302 (2009).
[2] H. Golnabi, M. Bahar, M. Razani, M. Abrishami, A. Asadpour, Optics and Lasers in Engineering, **45**, 12 (2007).
[3] U. S. Raikar, A. S. Lalasangi, V. K. Kulkarni, J. F. Akki, Optik - Int. J. Light Electron Opt. **122**, 89 (2011).
[4] R. P. McCue, J. E. Walsh, F. Walsh, F. Reagan, Sensors and actuators B, **114**, 438 (2006).
[5] S. Binu, V. P. Mahadevan-Pillai, V. Pradeepkumar, B. B. Padhy, C. S. Joseph, N. Chandrasekaran, Materials Science and Engineering C, **29**, 183 (2009).
[6] A. Leung, P. M. Shankar, R. Mutharasan, Sensors and Actuators B, **129**, 716 (2008).
[7] J-F. Chen, X-F. Chen, R-H. Xu, Y. Zhu, Y-F. Shi, X-Y. Zhu, Optics Communications. **281**, 3578 (2008).
[8] Yen-Liang Yeh, Optics and Lasers in Engineering. **46**, 666 (2008).
[9] M. Yokota, Y. Sato, I. Yamaguchi, T. Kenmochi, T. Yoshino, Meas. Sci. Technol. **15**, 143 (2004).
[10] P. Schiebener, J. Straub, J. M. H. Levelt-Sengers, J. S. Gallagher, J. Phys. Chem. Ref. Data. **19**, 677 (1990).

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