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Surface Plasmon Resonance Based Fiber Optic Sensor with Symmetric and Asymmetric Metallic Coatings: a Comparative Study

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Abstract: Surface Plasmon resonance based fiber optic sensors with symmetric and asymmetric metallic layer of gold coated on the fiber core are presented. The performance of both the sensors is analyzed experimentally in terms of sensitivity and detection accuracy. The experimental results obtained are compared with theoretical simulations obtained using N-layer model and Kretschmann configuration. The theoretical and experimental results are found to match qualitatively. It is shown that the sensitivity in the case of asymmetric coating is higher than that in the case of symmetric coating. The reverse is the case for detection accuracy. *Copyright © 2009 IFSA.*

Keywords: Optical fiber, Sensor, Surface Plasmon

1. Introduction

Sensors are becoming the essential part of the every upcoming new technology. Sensors, associated with the fiber optics have given birth to the several useful ways to sense the things whose sensing was not an easy task in the past [1]-[3]. Having some extra features such as smaller size, lightweight, immunity to electromagnetic interference and many more, has fascinated the researchers to develop the fiber optic sensors [1]. The phenomenon of surface Plasmon resonance is also playing an important role in sensing since past one decade [4]. This is because of high sensitivity and reliable procedure of the technique [5]-[9]. Surface Plasmon resonance based sensors have been widely applied for the quantitative detection of chemical and biological compounds such as pesticides, enzymes, nucleic acid etc [5, 6, 10]. Surface plasmons are basically the electromagnetic excitations, which propagate along the interface of the metal and a dielectric, decaying both in the metal as well as in the dielectric [2]. The metal cladded dielectric core fiber serves as a good candidate to support the surface Plasmon waves at the interface. These surface Plasmon modes are excited by the evanescent wave of the guided mode of the fiber if the wave vectors of the two are identical. This phase matching condition can be satisfied at one particular value of the wavelength or at a particular value of the angle of the incidence depending on the light source and the method of interrogation (spectral or angular) used. In the case of the optical fibers SPR sensors the spectral interrogation technique is generally used. The light from a polychromatic source is launched into the fiber with SPR probe in the middle and the spectrum of the transmitted power is recorded. The spectrum shows a dip at particular wavelength termed as resonance wavelength. This resonance wavelength is extremely sensitive to the medium around the metal layer. A slight variation in the refractive index of the sensing medium gives a substantial shift in the resonance wavelength, and this is the basic principle behind the SPR based fiber optic sensors. Many groups have tried to fabricate various designs of the fiber optic SPR probes to achieve better performance [5]-[7].

In the present paper the performance of surface Plasmon resonance based fiber optic sensors with symmetric and asymmetric metallic layer of gold have been studied. The performance has been analyzed experimentally in terms of sensitivity and detection accuracy. The experimentally obtained sensitivities have been compared with those obtained theoretically using N-layer model and Kretschmann configuration.

2. Experimental

2.1. Sensing Probe Preparation

A 20 cm of plastic clad silica (PCS) fiber of 600 μm core diameter and 0.37 numerical aperture was used for the fabrication of the SPR probe. A large core diameter fiber was used because of the following reasons: (a) light coupling is easier, (b) because of large surface area of the core the film can adhere easily, and (c) the fiber handling is easier. The jacket and the plastic cladding of the fiber were removed mechanically from 1 cm length of the middle portion of the fiber. The ends of the fiber were then prepared with a fine tungsten blade to make the end face perpendicular to the fiber axis. It was then cleaned with acetone and dried with a dryer. To deposit silver metal film on the unclad core the fiber was kept in vacuum chamber till the pressure inside it reaches to 10^{-6} Torr. Such a low pressure was achieved by first roughing the system for about 15 min followed by baking for 20 min. In the baking position, the heater was put on for around 1 hour after which the buffle valve was half opened. After 5 min, valve was opened completely till the desired amount of vacuum was achieved. Slowly and gradually the voltage was increased till whole silver kept in the molybdenum boat got evaporated. After this, the system was allowed to cool and the fiber was taken out of the chamber. The silver film thickness was about 50 nm. For the symmetric coating on the bare core of the fiber the fiber was rotated three times by 120 degrees. For asymmetric probe we kept another fiber for metallic coating and in this case the fiber was not rotated. It was kept only in one direction such that a crescent like structure of the metal layer is formed on the fiber core. The thickness of the gold layer in the center was kept 50 nm and then decreased gradually to zero at the edges. The cross sections of both the coatings on the fiber are shown in Fig. 1 (a) and (b). For measurement, the probe was fixed in a flow cell.

2.2. Sensing Medium

The solution of sucrose was used as the sensing medium around the metal film. Pure sucrose ($C_{12}H_{22}O_{11}$, molecular weight=342.30 g/mol) was purchased from Merck Specialties Private Limited

(India). The solutions of different concentrations of the sucrose were prepared in distilled water. Their refractive indices were measured by Abbe's refractometer.

(a) (b)

Fig.1. Cross Section of both the symmetric and asymmetric metal layer coated optical fiber sensors (a); the variation of thickness of the metal layer in the asymmetric metal coated fiber sensor (b).

2.3. Experimental Set Up

The experimental set up used for the characterization of the SPR probe is shown in the Fig. 2. The unpolarized light from a broad band (tungsten halogen) source is focused using a microscope objective of 0.40 numerical aperture at the input face of the fiber. The probe was mounted on a glass cell having the facility of inlet and outlet for the solution to be kept around the probe. The transmitted power from the output end of the fiber was fed to the spectrometer, which was further connected to a computer having the software to record the spectrum of the transmitted light. The resonance wavelength (dip) can then be estimated easily from the spectrum. The experiments were carried out for the sucrose solutions of different concentrations and in each case the resonance wavelength was determined. Such sets were obtained for both the SPR probes, symmetric and asymmetric.

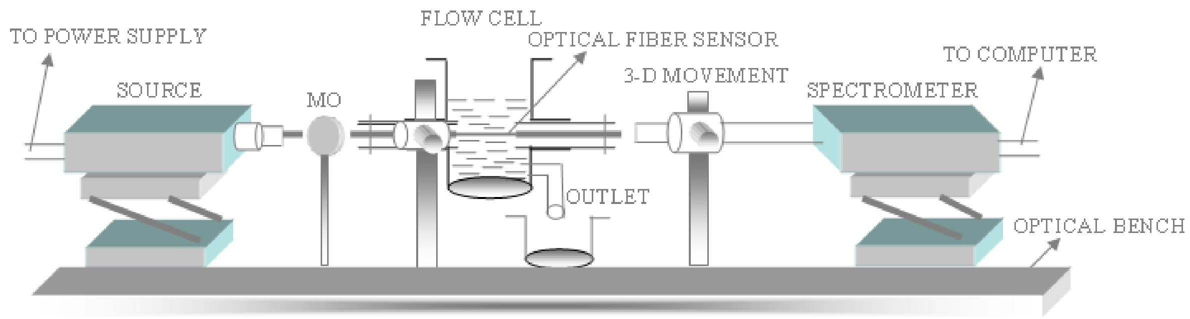

Fig. 2. Experimental set up for the measurement of the transmitted power at the output end of the fiber.

3. Theoretical

The theoretical modeling of the sensor is based on the principle of attenuated total reflection spectroscopy and Kretschmann's configuration. When a p-polarized light is launched at the one end of the multimoded optical fiber it gets guided inside the fiber if the angle of incidence at the core-cladding interface is greater than the critical angle of the fiber. The angular power distribution of all-guided rays launching depends on the angle (θ) of the ray and is given by [11]

$$dP \propto \frac{n_1^2 \sin\theta\cos\theta}{(1-n_1^2\cos^2\theta)} d\theta\,, \tag{1}$$

where n_1 is the refractive index of the fiber core. To determine the effective transmitted power N-layer matrix method was used [12]. If R_p is the reflection coefficient then the generalized expression for the normalized transmitted power (P_{trans}) in a fiber optic SPR sensor with symmetric metallic coating will be

$$p_{trans} = \frac{\int_{\theta_{cr}}^{\pi/2} R_p^{N_{ref}} \frac{n_1^2 \sin\theta\cos\theta}{(1-n_1^2 \sin\theta\cos\theta)} d\theta}{\int_{\theta_{cr}}^{\pi/2} \frac{n_1^2 \sin\theta\cos\theta}{(1-n_1^2 \sin\theta\cos\theta)} d\theta}\,, \tag{2}$$

where

$$N_{ref} = \frac{L}{D_c \tan\theta} \tag{3}$$

$$\theta_{cr} = \sin^{-1}\left(\frac{n_{cl}}{n_1}\right) \tag{4}$$

N_{ref} represents the total number of reflections performed by a ray making an angle θ with the normal to the core-metal layer interface in the sensing region while L and D_c represent the length of the exposed sensing region and the fiber core diameter, respectively. The θ_{cr} is the critical angle of the fiber, whereas n_{cl} is the refractive, index of the fiber cladding. In equation (2) we have considered all guided rays and have integrated from θ_{cr} to $\pi/2$.

To calculate the transmitted power for the asymmetric structure we have taken one more integral for metal thickness variation, which has the limits from maximum value of the thickness to zero as shown in Fig. 1 (b). The normalized effective transmitted power for asymmetric half-coating of the bare core of optical fiber is given as

$$p_{trans} = \frac{\int_{-a}^{0}\int_{\theta_{cr}}^{\pi/2} R_p^{N_{ref}} \frac{n_1^2 \sin\theta\cos\theta}{(1-n_1^2 \sin\theta\cos\theta)} d\theta dx}{\int_{-a}^{0}\int_{\theta_{cr}}^{\pi/2} \frac{n_1^2 \sin\theta\cos\theta}{(1-n_1^2 \sin\theta\cos\theta)} d\theta dx}\,, \tag{5}$$

where

$$N_{ref} = \frac{L}{4a\tan\theta} \tag{6}$$

and a is the radius of the core. Metal layer thickness variation is given as

$$d' = \sqrt{x^2 + b^2\left(1 - \frac{x^2}{a^2}\right)} - a\,, \tag{7}$$

where, $b=a+\Delta$ and Δ is the maximum thickness. It may be noted that R_p, the reflection coefficient, in equation (5) depends on film thickness. In fiber optic SPR based sensor, a polychromatic source is used and hence wavelength interrogation method is used. To know the resonance wavelength, the transmitted power is plotted with wavelength.

4. Results and Discussions

As mentioned above, experiments were carried out for both the symmetric and asymmetric metal coated fiber optic probes. The SPR spectra were obtained for different concentrations and hence the refractive indices of sucrose solution in distilled water. The SPR spectrum for 1.339 refractive index of sucrose solution for symmetric coating (full coating) is shown in Fig. 3. The spectrum obtained contains a dip at a particular value of the wavelength known as the resonance wavelength. Similar kinds of results have been reported in the literature for symmetric coating.

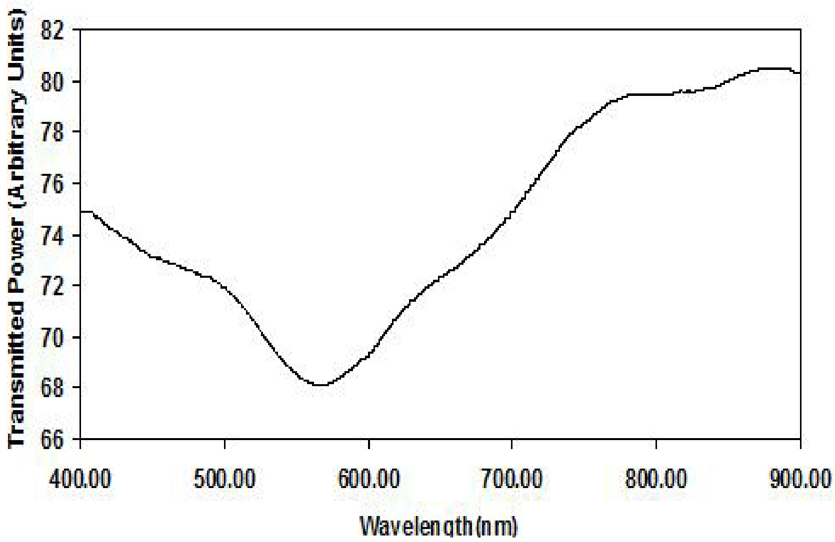

Fig. 3. Variation of transmitted power (arbitrary units) as a function of wavelength for1.339 as the refractive index of the sensing medium in the case of symmetric coating.

Fig. 4 shows the SPR spectrum obtained for 1.362 as the refractive index in the case of asymmetric coating. The SPR spectrum obtained from the asymmetric coating shows multiple dips. It is because the asymmetry in the structure leads to the excitation of surface Plasmon modes of higher azimuthal orders (m>1). Depending upon the resonance conditions the dip in the transmitted power is observed at different values of the wavelength. The sharpest and the deepest dip correspond to the excitation of the fundamental surface Plasmon mode while the others at the lower wavelength sides are because of the higher order modes. Hence if one compares this SPR spectrum with that shown in Fig. 3, one will notice a difference at lower wavelength region. In the case of asymmetric coating there is a small dip around 450 nm which one does not see in the case of symmetric coating. These experiments were repeated with sucrose solutions of different concentrations and the corresponding shifts in the resonance wavelength were measured. The curves were then plotted between the resonance wavelength and the refractive indices for both symmetric and asymmetric coatings. For asymmetric coating, the dip at larger wavelength side was used for this plot. It was found that on increasing the refractive index the resonance wavelength increases, these results are similar to those reported in the literature. This is quite obvious since on increasing the refractive index of the sensing medium the wave vector of the surface Plasmon mode increases and this leads the resonance condition to be satisfied at some higher value of the wavelength of the incident wave. From these curves, the sensitivity which is defined as the change in the resonance wavelength per unit change in the refractive index of the sensing medium was calculated by measuring the slope of the nonlinear curve at different refractive indices. A plot of sensitivity against the refractive index of the sensing medium is shown in the Fig. 5 for both symmetric (full) and asymmetric (half) coating. The figure shows that as the refractive index of the sensing region increases the sensitivity increases for both symmetric and asymmetric metal coated fiber optic probes. However the sensitivity is more in the case of asymmetric coating.

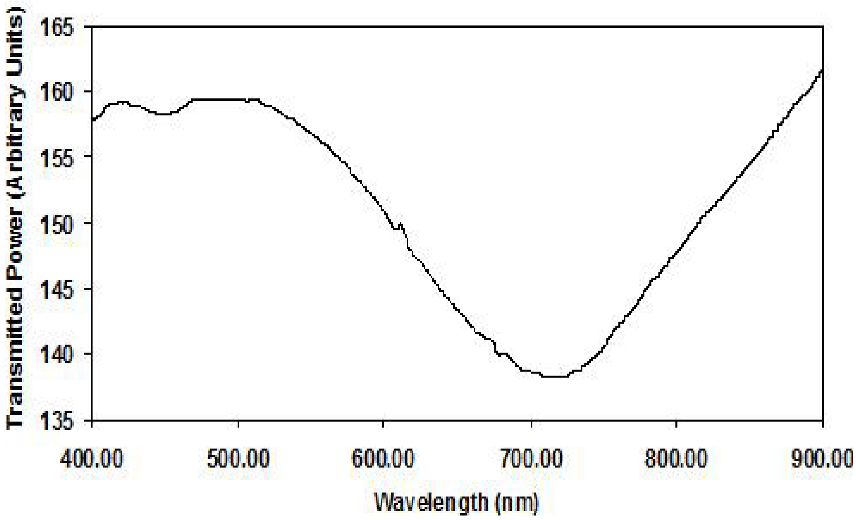

Fig. 4. Variation of transmitted power (arbitrary units) as a function of wavelength for 1.362 as the refractive index of the sensing medium in the case of asymmetric coating.

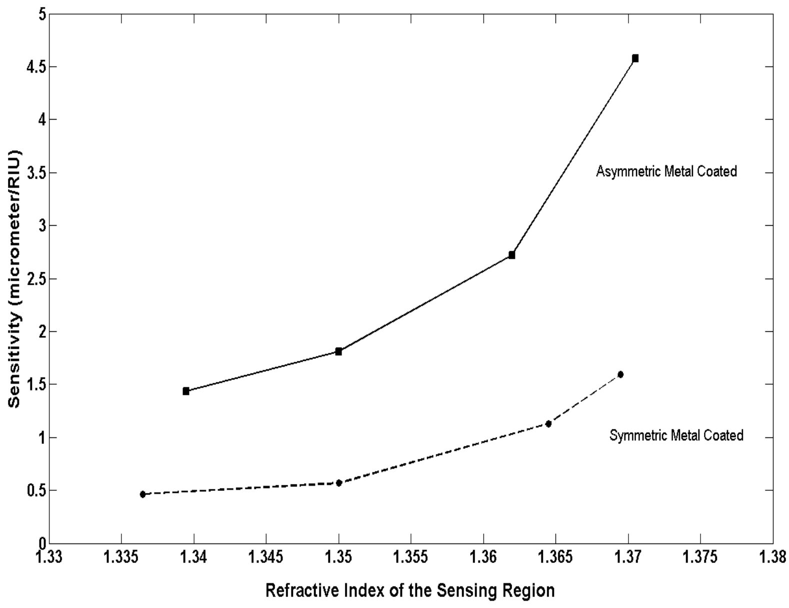

Fig. 5. Experimental variation of the sensitivity of the fiber optic sensor for both the symmetric and asymmetric metal structure.

The experimental results presented above were also verified using N-layer model discussed in Section 3. For simulation following values of the parameters were used: numerical aperture of the fiber = 0.37, fiber core diameter = 600 μm, gold layer thickness = 50 nm. Sellmeier relation was used for the wavelength dependence of the refractive index of the core of the fiber. The wavelength dependence of the cladding refractive index comes automatically as the numerical aperture was taken to be a fixed value. The wavelength dependence of the dielectric constant of the gold was taken from the Drude model [11]. The SPR curves were calculated using equations. (2) and (5) for symmetric and asymmetric coatings respectively. Fig. 6 shows the SPR curves for asymmetric coating for three different refractive indices of the sensing region. It may be noted from the figure that as the refractive index increases the SPR wavelength shifts to the higher wavelength. Further, a dip is obtained at lower wavelength similar to that obtained experimentally in Fig. 4. From SPR curves obtained for different values of the refractive indices of sensing region the sensitivities were calculated for both symmetric and asymmetric coatings.

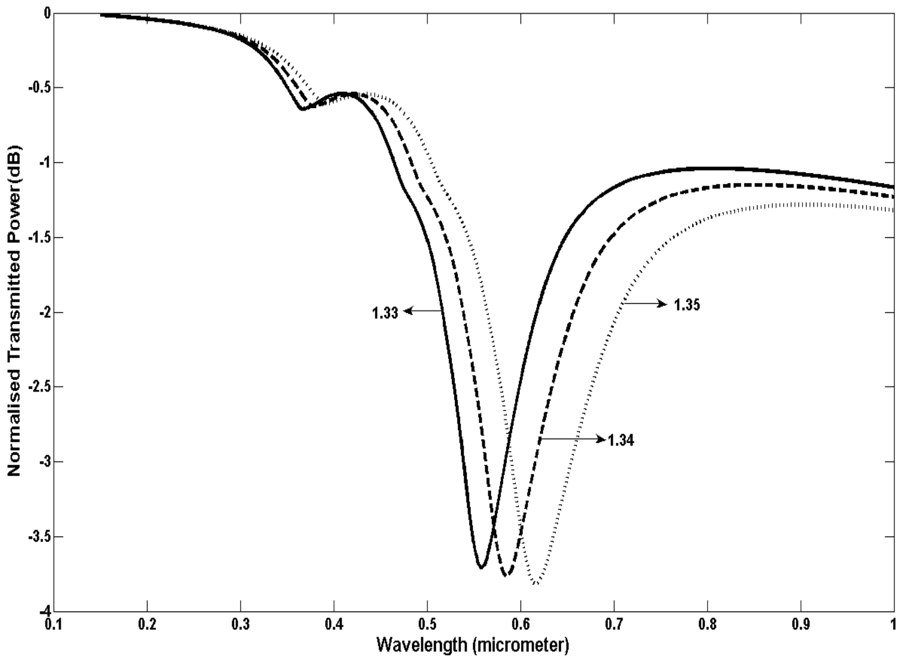

Fig. 6. Variation of the calculated transmitted power with the wavelength for asymmetric metal layer coated fiber optic sensor.

Fig. 7 shows the variation of sensitivity with refractive index for symmetric and asymmetric coatings. It may be noticed that the sensitivity obtained from the theory is little bit higher than that obtained experimentally. This is because we have not taken the skew rays into account in our calculations whose effect would be to reduce the sensitivity of the fiber optic sensor [14]. As shown in Fig. 7, the sensitivity of the fiber optic SPR sensor with asymmetric metallic coating is higher than the symmetric metal coating. This is similar to the results obtained from the experiment. Such a behavior can be explained from the concept of radiation damping in the surface Plasmon. The resonance dip is because of the destructive interference of the incident light and the backscattered light from the fiber core and metal layer interface. Due to the asymmetry in the structure the thickness varies from zero to a maximum value and hence it leads to the more amount of the backscattered light to interfere with the incident wave making it almost zero value. Due to this a stronger coupling takes place between incident wave and the surface Plasmon wave. Therefore a slight variation in the sensing region refractive index gives a substantial amount of change in the resonance wavelength and hence sensitivity is bound to increase. The drawback with this asymmetric metal structure is that its detection accuracy is poor as compared to symmetric structure for a fixed refractive index of the sensing region. This is because of the greater amount of absorption of the incident wave in the case of asymmetric structure, which makes the SPR curve broad.

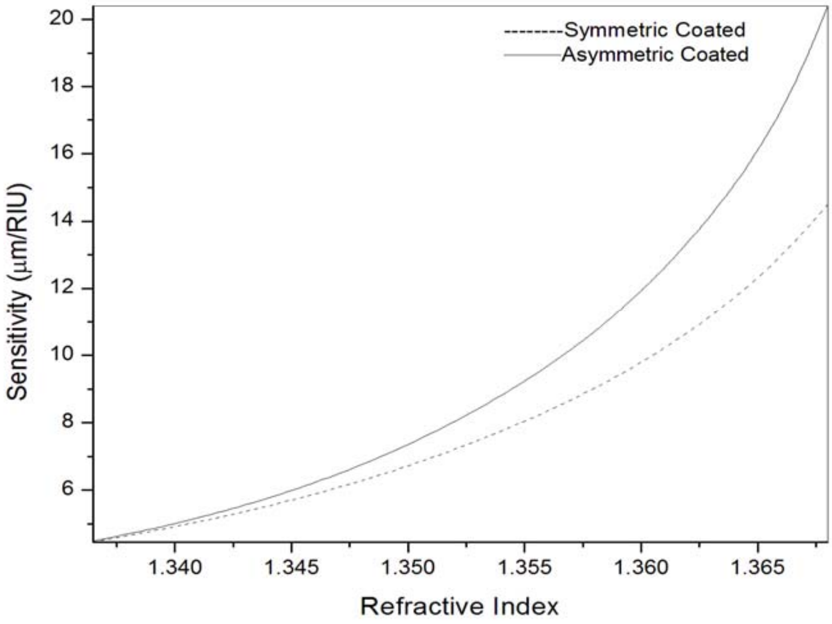

Fig. 7. Theoretical variation of the sensitivity of the sensor for symmetric structure.

5. Conclusion

The study of the surface Plasmon resonance based fiber optic sensors with symmetric and asymmetric metallic layer coated on to the fiber core has been carried out. The experimental results predict higher sensitivity for fiber optic SPR based sensor with asymmetric coating and for a given refractive index of the sensing medium. The experimental results are found to agree with the theoretical ones obtained using N-layer model.

Acknowledgments

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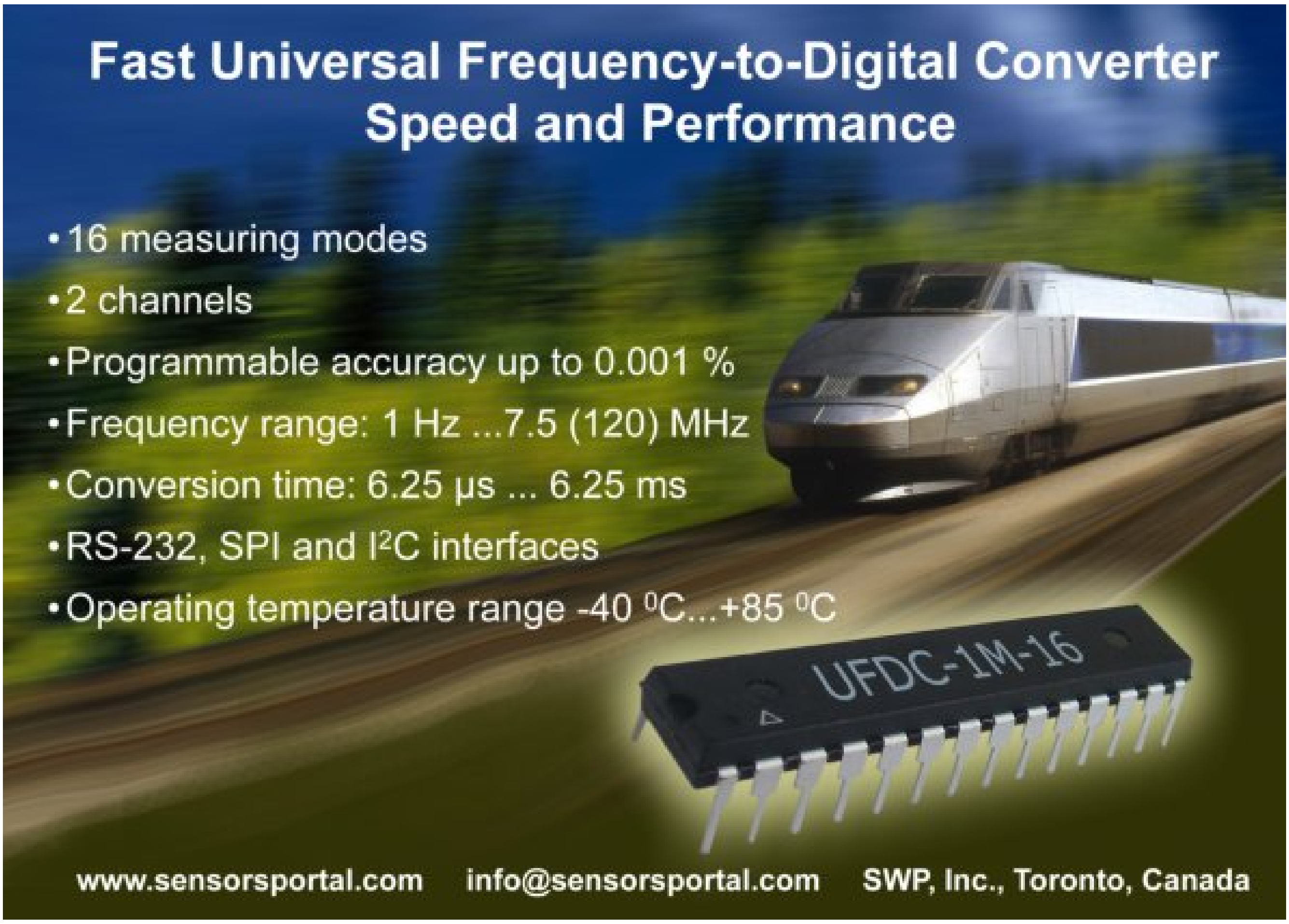

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