2008

Photonic Nano-Structures For Water Quality Monitoring

Mikhail Vasiliev
Edith Cowan University

Kamal Alameh
Edith Cowan University

10.1117/12.786319 This article was originally published as: Vasiliev, M. , & Alameh, K. (2008). Photonic Nano-Structures For Water Quality Monitoring. Proceedings of 19th International Conference on Optical Fibre Sensors. (pp. 70045E-1 to 70045E-4). Perth, Western Australia. SPIE. Original article available here

Photonic nano-structures for water quality monitoring

Mikhail Vasiliev and Kamal Alameh
Electron Science Research Institute, 100 Joondalup Drive, Joondalup, WA, 6027, Australia.

ABSTRACT

We propose a new type of sensors suitable for water quality testing and for monitoring water contamination levels in domestic, industrial and environmental applications. The proposed sensing scheme uses Fourier transform cavity-enhanced absorption spectroscopy and novel compact sensing elements based on nanostructured photonic crystal-type optical coatings enabling the sensitive Fourier-domain processing methodology and maximising the absorption path length within the measurement system. The measurement scheme is shown to be suitable for the determination of small changes in the water absorption coefficients at a discrete set of wavelengths in the visible spectral region in response to small concentrations of pollutants with high sensitivity. The proposed sensors are expected to provide real-time information on the water contamination levels, as well as potentially the types of substances dissolved.

Keywords: Water quality sensing, environmental monitoring, photonic crystal mirrors, cavity-enhanced absorption spectroscopy.

1. INTRODUCTION

In recent years, there has been an increased interest among researchers in investigating new techniques and systems for testing the quality of drinking water, as well as monitoring the quality of environmental water resources [1-4]. Testing of the optical clarity of water (usually done in analytical laboratories by means of spectrophotometry) through the absorption spectrum analysis allows detection of various dissolved chemical pollutants through their spectral "fingerprints", as well as measurement of pollutant concentrations. Among the technologies developed for improving the sensitivity and accuracy of absorption spectra measurement in weakly-absorbing media, Fourier transform cavity-enhanced absorption spectroscopy is one of the most sensitive and promising, and the detection of very small (several parts-per-billion by volume) concentrations of sulfur dioxide in gases emitted by vehicles has been demonstrated recently with this technique [5]. We propose a new design of miniature cavity-type water quality sensing elements using nano-structured optical coatings as Fabry-Perot (FP) cavity mirrors, and suitable for the accurate measurement of small absorption changes within weakly-absorbing cavity media at a discrete set of optical wavelengths. The principal diagram of a sensing element proposed is shown in Fig. 1, where the operation of a cavity-enhanced absorption sensor in the transmission mode is sketched.

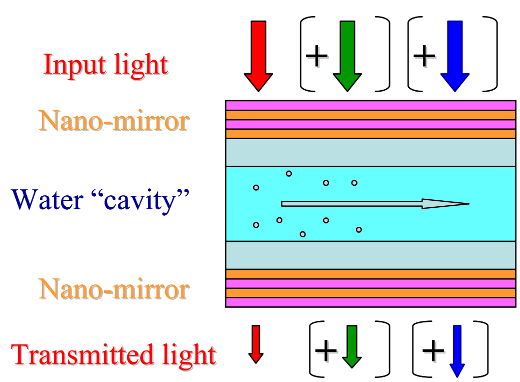

Fig. 1. Schematic diagram of the sensing element proposed for water quality monitoring using discrete-wavelength cavity-enhanced absorption spectroscopy. An array of sensing elements is required for multi-wavelength interrogation; however, a single mini-cavity element is shown for simplicity. The cavity boundaries can be formed by either the substrate or film surfaces. The water is externally pumped through the cavity, and the precision mechanical spacers (not shown) are necessary to permanently align the system composed of two nano-structured coatings on glass substrates.

19th International Conference on Optical Fibre Sensors, edited by David Sampson, Stephen Collins, Kyunghwan Oh, Ryozo Yamauchi, Proc. of SPIE Vol. 7004, 70045E, (2008) 0277-786X/08/$18 doi: 10.1117/12.786319

2. SENSING PRINCIPLE AND THE SIGNAL PROCESSING SCHEME

The absorption spectrum of pure water (shown in Fig. 2) is characterised by very small absorption coefficients (of less than 10^{-2} cm^{-1}) in the visible region, and has a minimum of absorption coefficient near 420 nm. The changes in the absorption spectrum caused by the dissolved chemical pollutants are also small at the low contaminant concentrations, which necessitates the use of sensitive measurement schemes, and (preferably) large absorption paths. In the UV, and also in the blue-green regions of spectrum, the water itself is highly transparent, but at the same time, most dissolved compounds (organic and inorganic) have a significant absorption, exceeding that of pure water, which makes this spectral region very attractive for the sensing and monitoring of low pollutant concentrations using absorption spectroscopy. Moreover, due to the strong wavelength dependency of the absorption spectra of most known pollutants in the optical region, the spectral discrimination of the different pollutant types is possible, leading to the possibility of analyzing the contamination content using absorption spectroscopy.

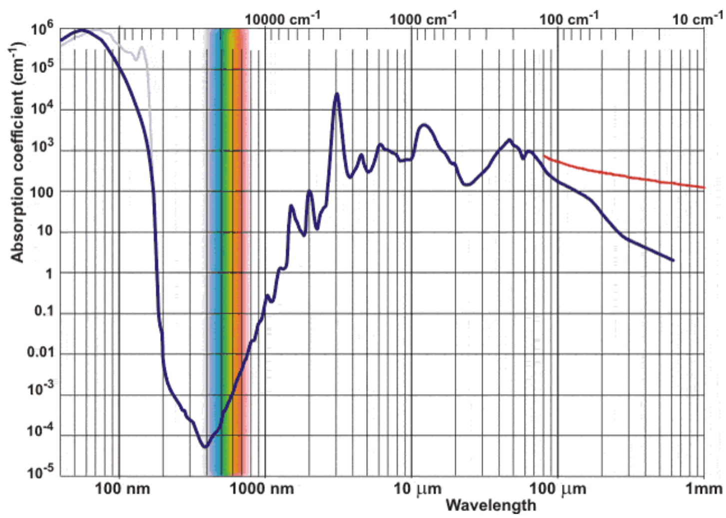

Fig. 2. Absorption spectrum of pure (distilled) water [6].

We propose a new type of the absorption sensing element, which combines the advantages of miniature size, low manufacturing costs, suitability for both laboratory-based and field measurements, cavity-enhanced multi-pass absorption path, and the suitability for sensitive Fourier-domain signal processing. The latter is based on the spectral comb-type filtering of the transmitted source light by the high-finesse Fabry-Perot cavity formed by two nano-structured optical coatings sputtered onto glass substrates. The photodetector signal spectrum produced by the light transmitted through the sensor filled with a weakly-absorbing medium (water) will contain the differential (beat) frequency (in the RF domain) caused by the heterodyne beating of the multiple spectrally-narrow optical transmission peaks of the FP structure.

A sample design of nano-structured cavity mirror coatings suitable for 473 nm sensor operation is shown in Fig. 3, together with the comb-type spectral response of the proposed device to white-light illumination. In addition, the sensitivity of the sensor is also illustrated in Fig. 3 by means of showing the effect of a water absorption coefficient change from 0.0005 cm^{-1} (chemically pure water at 473 nm) to 0.0055 cm^{-1} (contaminated water) on the spectral intensity distribution of the light transmitted within the spectral comb peaks. As demonstrated by our modelling results, the effect of small absorption coefficient changes (on the scale comparable to the very low absorption of the chemically pure water) within the cavity medium is relatively small, however, it is easily measurable by the sensitive photodetector circuitry (the magnitude of the transmission change shown is several percent of the peak transmitted intensity). With Fourier-transform heterodyne processing, due to the small transmitted intensity changes occurring within a number of transmission peaks simultaneously, the absorption coefficient changes on the scale smaller than the absorption of pure water are expected to be measurable. The data reported in [4] shows that at 473 nm, the oceanic water absorption changes on the scale of ΔA= 0.001–0.004cm^{-1} were caused by only 0.14–1.3 ppb (mg/m^3) of planktonic chlorophyll present in the water.

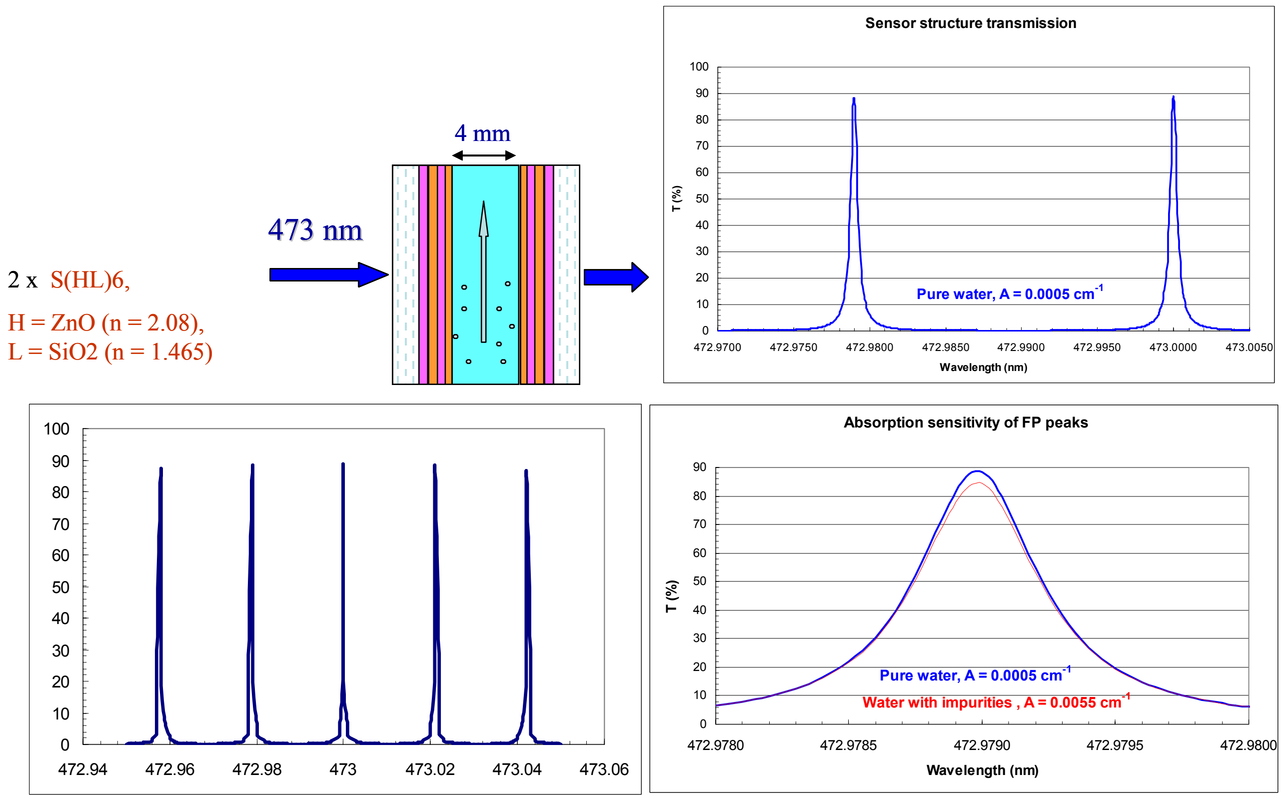

Fig. 3. The mode of operation of the proposed sensors, a sample design of the cavity mirrors and the sensing element geometry, and the cavity transmission response to the uniform-intensity broadband illumination. Also shown is the spectral intensity distribution within a single narrow comb peak of structure transmission, and its variation in response to a small (ΔA = 5×10^{-3} cm^{-1}) change in the water absorption coefficient at 473 nm, caused by the water contamination. The cavity mirrors are formed by two identical nano-structured periodic films of structure S(HL)6, where S = Corning 7059 glass substrate, H = Zinc oxide (ZnO), and L = Silicon dioxide (SiO_2); all layers have an optical thickness of a quarter of the design wavelength (473 nm). The thickness of high-index (H) individual layers is 56.9 nm, the thickness of low-index (L) layers is 80.7 nm, and the total structure thickness is only 0.826 μm. The water-filled cavity width is an easily-adjustable design parameter, and is set to 4 mm in the current design.

The overall signal processing scheme and also our roadmap for the future implementation of the proposed absorption sensor is illustrated in Fig. 4, where a blue diode-pumped solid-state (DPSS) laser emitting at 473 nm within a spectral linewidth of about 0.2 nm is shown as a light source of choice for the experimental demonstration of the proposed concepts.

The experimental implementation of the proposed nano-structured cavity-enhanced absorption sensors is still in its initial stages, however, we have already established the technology for the manufacture of photonic crystal-type periodic multilayered nanostructures with precisely-controlled layer thicknesses, capable of delivering the designed spectral response features in the spectral regions of interest for the proposed application. The detailed results of sensor system development will be reported elsewhere.

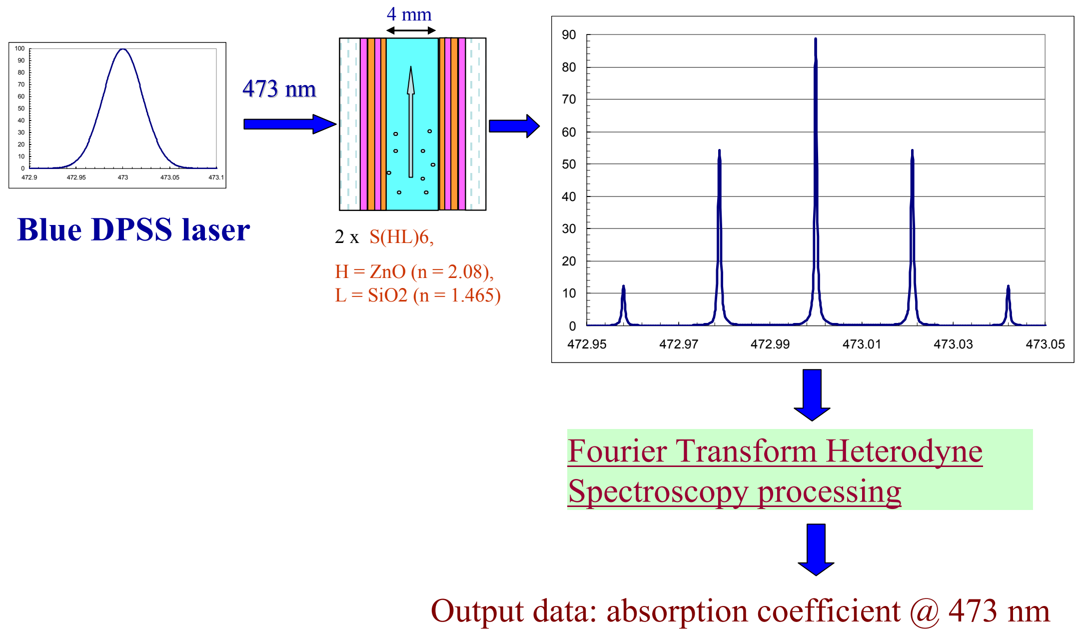

Fig. 4. The signal processing scheme for nanostructure-based cavity-enhanced absorption sensors suitable for the measurement of changes in the absorption coefficient of water caused by dissolved contaminants.

3. CONCLUSION

In this paper, we have proposed a new type of optical sensors suitable for the measurement of optical absorption coefficients in weakly-absorbing media, water quality testing, and for monitoring the water contamination levels in a variety of applications. The proposed sensing scheme uses Fourier transform cavity-enhanced absorption spectroscopy and novel compact sensing elements based on nano-structured photonic crystal-type optical coatings. The measurement scheme has been shown to be suitable for the determination of small changes in the water absorption coefficients at a discrete set of wavelengths in the visible spectral region in response to small concentrations of absorbing pollutants, with high sensitivity. The proposed sensors are particularly attractive for environmental monitoring and food processing, and are expected to provide real-time quantitative information on the chemical contamination levels in drinking water, as well as potentially the types of substances dissolved.

REFERENCES

[1] P. Dress, M. Belz, K. F. Klein, K. T. V. Grattan, and H. Franke, "Water-Core Waveguide for Pollution Measurements in the Deep Ultraviolet," Appl. Opt. **37**, 4991-4997 (1998).

[2] A. A. Ruth, J. Orphal, and S. E. Fiedler, "Fourier-transform cavity-enhanced absorption spectroscopy using an incoherent broadband light source," Appl. Opt. **46**, 3611-3616 (2007).

[3] W. S. Pegau, D. Gray, and J. R. V. Zaneveld, "Absorption and attenuation of visible and near-infrared light in water: dependence on temperature and salinity," Appl. Opt. **36**, 6035-6046 (1997).

[4] Hubert Loisel, Dariusz Stramski *et al*, "Comparison of the ocean inherent optical properties obtained from measurements and inverse modeling," Appl. Opt., **40(15)**, 2384-2397, 2001.

[5] J T Pisano *et al,* **"**A UV differential optical absorption spectrometer for the measurement of sulfur dioxide emissions from vehicles," Meas. Sci. Technol*.* **14**, 2089-2095, 2003.

[6] Martin Chaplin, "Water structure and science," http://www.lsbu.ac.uk/water/vibrat.html, sighted in Nov 2007.