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Hybrid Photonic-Plasmonic Waveguides (HPWG) for Hydrogen Sensing

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Summary:

This contribution describes an HPWG structure, comprising a dielectric waveguide, a buffer layer and a metallic or semi-metallic sensing layer stack (metallic waveguide). By using the HPWG as a polarization selector, this layer stack works as a chemical sensor whose signal is independent of intensity variations of the incoming light and is therefore optically self-calibrated. Hydrogenation of the sensing layer stack changes its effective light absorption coefficient and/or refractive index upon changes of the hydrogen partial pressure in the environment. We demonstrate by modeling the optical response of the HPWG that, by tuning the thickness of the buffer layer and the respective layers (materials composition, thickness) of the sensor stack, it is possible to build optically self-calibrated HPWG structures to be used as sensors for hydrogen.

Keywords: hydrogen sensing, waveguide, photonics, plasmonics, HPWG

Background, Motivation and Objective

Dielectric (or photonic) waveguides are microstructures used in photonics to guide light by total internal reflection, similarly to optical fibers. In contrast to optical fibers, dielectric waveguide do not generally have a circular cross-section, and are deposited, machined, or ion-implanted in/on a substrate. Prominent examples of such waveguide are Silicon-on-a-substrate (SOI) waveguide, i.e. a –comparatively high refractive index- Si waveguide of rectangular cross-section obtained by lithography on a –comparatively lower refractive index- SiO_2 substrate.

Metallic (or plasmonic) waveguides are metallic microstructures on a dielectrics. In this case, light propagates near the metal surface, either at the metal-dielectric interface, or in a gap of the metal. Typical metal used is silver. Losses for metallic waveguides are usually much higher than for dielectric waveguides, but the higher confinement allows smaller structures (rings, sharp turns). Hybrid (photonic-) plasmonic waveguides (HPWG) are structures that use a combination of both structures introduced above.[1]

The materials used in most reported hydrogen sensors is Palladium (Pd).[2] If an optical readout scheme is used, Magnesium (Mg) alloyed with transition metals offers a higher optical contrast between the metallic and hydride states,[3] and also allow to decrease the lowest detection level (LOD).[4] The sensing layer can be e.g. deposited at the tip of an optical fiber and operated in reflection mode.[5] This design relies on the change of light amplitude induced by hydrogen absorption. Any other variation of the light intensity, such as from the light source or change in optical coupling could therefore induce errors in the hydrogen reading if not properly addressed. In this contribution, we propose to use HPWG waveguide structures for optical hydrogen sensing, providing an intrinsic referencing of the light intensity.

General Principle of Operation

As shown in Figure 1, the TE mode is guided by the dielectric waveguide and its intensity is relatively insensitive to the sensor stack.

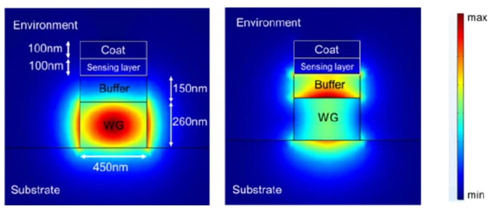


Figure 1. Cross-section of proposed sensor structure. Color code: Electric field magnitude for the HPWG (COMSOL, RF module). left, transverse magnetic (TE) mode, right, transverse electric (TM) mode. Substrate and Buffer: SiO_2 (n = 1.5), WG = Waveguide: Si (n = 3.44), Sensor stack: Sensor = $Mg_{70}Ti30H_x$ and Coat: Pd (n = 3.2, k = 8.15). Environment: air (n = 1).

The TM mode is mostly guided within the buffer region and is therefore in first order sensitive to variation of absorption coefficient of the sensor stack. The attenuation per HPWM length of the TM mode can be tuned by changing the thickness of the buffer layer. The TM mode is also sensitive to the refractive index of the sensor stack. The attenuation per HPWG length is lower for the transverse electric (TE) propagation mode than for the transverse magnetic propagation mode, and this for all values of the absorption coefficient of the sensor stack. Hence the transmission of the TE mode may be used as an internal light intensity reference, and the transmission of the TM as the sensing signal.

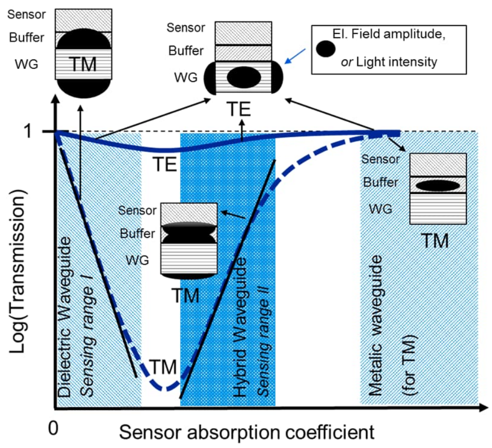


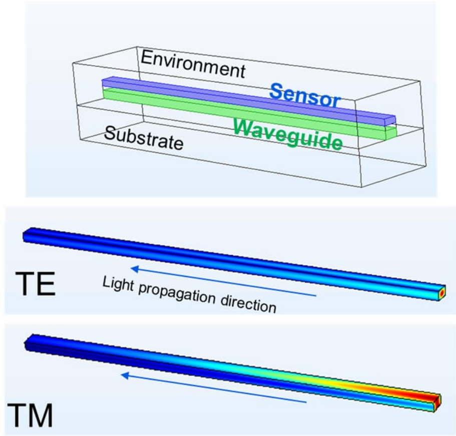
Figure 2. Principle of operation and sensing ranges of proposed HPWG sensor. Transmitted light intensity as a function of optical absorption coefficient of the sensor stack (for constant refractive index) WG: dielectric waveguide, TE: transverse Electric mode, TM: transverse magnetic mode.

Results

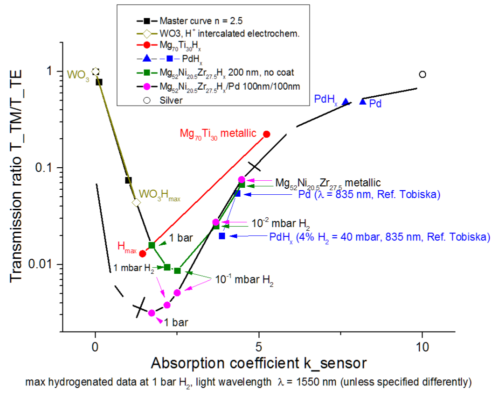
Figure 3 shows the ratio of the light intensities TM/TE for a simple linear waveguide geometry. We take a few hydrogen absorbing materials as examples to exemplify the sensing range I (dielectric waveguide) with proton-intercalated tungsten trioxide (WO_3), or sensing range II (HPWG) with Pd-coated Mg-Ni-Zr or Pd-coated Mg-Ti layers, covering a range of H_2 pressures from 10^{-3} to 10^2 mbar (not shown here).

Summary

We presented a HPWG readout concept for optical hydrogen sensing that is independent of the light source intensity. It is compatible with protection layers on top of the sensor stack to ensure sensitivity only to the desired species (H_2) and resistant to adverse species (H_2O, O_2). It is also cost-effective, as it works at a telecom wavelength of 1550 nm, for which low-cost components are available.



(a)



(b)

Figure 3. (a) 3D view of the HPWG structure with (color code) light intensity for TE and TM mode through waveguide. (b) Ratio of the transmission of TM and TE modes for various hybrid waveguide structures as a function of the absorption coefficient of the sensing layer. Refs. for optical properties: Pd [6], WO_3[7], Mg-Ti, Mg-Ni-Zr: own measurements as in [3],[4]. Silver: http://refractiveindex.info/

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