

INTEGRATED OPTICAL WAVEGUIDE INTERFEROMETER

- 5 The present invention relates to an integrated optical waveguide interferometer for evanescent sensing of chemical and/or physical quantities, comprising a substrate carrying a waveguide layer structure provided with
- 10 - a first waveguide core layer sandwiched between two first claddings layers formed by a first lower and a first upper cladding layer, of a lower refractive index than the first waveguide core layer,
- 15 - a second waveguide core layer sandwiched between two second claddings layers formed by a second lower and a second upper cladding layer, of a lower refractive index than the second waveguide core layer,
- 20 - a splitter and a combiner for optically coupling said first and second waveguide core layers at first and second junctions, respectively.

Such an integrated optical waveguide interferometer is known from United States patent publication no. 6,240,226 (Lucent Technologies, Inc.). The integrated optical waveguide

25 interferometer described therein is of the Mach-Zehnder type. This known Mach-Zehnder interferometer includes a first waveguide core channel and a second waveguide core channel, both brought close together at a first directional coupler and a second directional coupler. The first

30 waveguide core channel is surrounded at all sides not in contact with the substrate by a first cladding and the second waveguide core is surrounded at all sides not in contact with the substrate, by a second cladding. The first

cladding includes a section of a polymer cladding in contact, at all sides not in contact with the substrate, with the first waveguide core channel between the first and the second directional couplers. Outside the polymer

5 section, the first waveguide core channel is surrounded by a standard cladding material. The second waveguide core is similar to the first waveguide core except that a standard cladding material is employed throughout its length. The polymer cladding has an index of refraction that varies with
10 temperature. The temperature of the section of polymer cladding is adjusted to cause a corresponding change in the phase of light flowing through the first waveguide core bounded by the polymer cladding to effect a desired switching or modulation of the light.

15 It is noted that the present invention is not limited to a Mach-Zehnder interferometer, but also extends to other interferometers, such as a so-called Michelson interferometer or a so-called Young interferometer. However,
20 the present invention particularly relates to a so-called planar optical waveguide interferometer, that is an interferometer consisting of a thin transparent core film sandwiched between transparent cladding layers with lower refractive indices that confine the propagating light in the
25 core film such that a large evanescent optical sensing field is present in the cladding layers, wherein such a waveguide stack is preferably deposited on a flat smooth substrate for the purpose of mechanical stability. Further, in the framework of the present invention the splitter and the
30 combiner do not only refer to a first and a second directional coupler, as described in said United States patent publication no. 6,240,226, but also refer to, for example, a first micro-optic beam splitting cube and a

second micro-optic beam splitting cube, or a first Y-branch splitter and a second Y-branch splitter, respectively. Finally, the term "evanescent sensing" as used above is a term well-known in the art, that is applying a chemically sensitive material as a cladding layer within a window obtained by locally removing the originally applied cladding layer.

A disadvantage of an integrated optical waveguide interferometer known from said United States patent publication no. 6,240,226 is that, dependent on the technical field of use, the efficiency and accuracy in sensing applications do not meet today's wishes. For sensing applications a large evanescent field is required, which forces the core to be thin and predominantly planar with no or only shallow ridge structuring. A polymer cladding section will therefore cover only the upper part of the waveguide core. Consequently, thermo-optic modulation will not be as efficient for a polymer cladding surrounding the core at all sides not in contact with the substrate.

Therefore, it is an objection of the invention to improve the prior art and to accomplish that objective an interferometer of the type mentioned in the preamble according to the invention is characterized by

- a modulation section of a polymer cladding material included in one of the first upper cladding layers and/or included in one of the second upper cladding layers, the polymer cladding material covering an identifiable area of said first waveguide core layer and/or said second waveguide core layer between the first and second junctions, said polymer cladding

material having an index of refraction between 1.46 and 2.5 that varies with temperature, thereby changing the phase of radiation propagating through said first and second waveguide core layers,

- 5 - means for raising and lowering the temperature of said polymer cladding material.

An important feature is thus that a modulation section is obtained by means of an asymmetric layer structure equipped with said section of polymer cladding material having a higher refractive index than the lower cladding layer, selected such that the evanescent field is close to "cut-off". This means that the evanescent field is pulled into said section of polymer cladding material, whereas thermal changes in its refractive index will have a strong effect on the effective refractive index of the structure.

Particularly, said interferometer according to the invention satisfies the equations in said modulation section:

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- (1) $n_c > n_s$
- (2) $V = 2\pi(h/\lambda)(n_f^2 - n_c^2)^{1/2}$
- (3) $r = (n_f^2 - n_s^2) / (n_f^2 - n_c^2)$

25 with

- n_c being the refractive index of the first upper cladding layer and/or the second upper cladding layer;
- n_s being the refractive index of the first lower cladding layer and/or the second lower cladding layer;
- 30 - n_f being the refractive index of the first core layer and/or the second core layer;
- h being the thickness of the first core layer and/or the second core layer;

- λ being the optical wavelength;
- V varying between 0.1 and 4 for $r > 1.1$.

An important feature of a preferred embodiment of the present interferometer is an optimization of the thermo-optic efficiency (required power for a given effective index change) by a choice of the refractive index of the polymer cladding, n_c , such that the optical mode has a large evanescent field in that cladding. The conditions for that are as follows:

- 1) The refractive index of the polymer cladding, n_c , is close to that of the core n_f . This induces the cut-off of the mode with strong field expansion out of the core. A measure for this condition is the value of the so-called V-parameter: $V = 2\pi(h/\lambda)(n_f^2 - n_c^2)^{1/2}$

For a symmetric waveguide having a identical refractive index for the polymer upper cladding and the lower cladding the cut-off condition for the fundamental mode is at $V = 0$. The first order mode can exist starting from $V = \pi$ (note that the waveguide should stay monomodal).

For a highly asymmetric waveguide, having a large refractive index difference between the polymer (upper) cladding and the lower cladding, n_s , the cut-off of the fundamental mode occurs at $V = \pi/2$. The first order mode can exists starting from $V = 3\pi/2$.

- 2) The refractive index difference between the polymer upper cladding and the lower cladding, n_s , is large (high asymmetry). This induces the field expansion to occur exclusively in the polymer

cladding. A quality measure for this condition is the ratio of the optical power at the boundaries of the core with the polymer cladding (P_c) and with lower cladding (P_s). For the TE modes this ratio,

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$$P_c / P_s, \text{ is: } P_c / P_s = r = (n_f^2 - n_s^2) / (n_f^2 - n_c^2)$$

Therefore, a suitable choice for V would be in the range between $V = 0.1$ and $V = 4$ in combination with a value for r in the range of $r > 1.1$.

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Preferably, said polymer cladding material is at least substantially made from a material selected from the group consisting of poly pentabromophenyl methacrylate, poly pentabromophenyl acrylate, poly pentabromobenzyl methacrylate, poly pentabromobenzyl acrylate, poly 2,4,6-tribromophenyl methacrylate, polyvinylphenyl sulfide, poly 1-naphthyl methacrylate, poly 2-vinylthiophene, poly 2,6-dichlorostyrene, poly N-vinylphthalamide, poly 2-chlorostyrene en poly pentachlorophenyl methacrylate. In the alternative, said polymer cladding material is at least substantially made from a material selected from the group consisting of a polymer based on aromatic benzene rings and a polymer based on fused aromatic rings, such as an SU-8 epoxy monomer or an aromatic polyimide. Preferably, high refractive index particles have been added to the material of said polymer cladding material in order to increase the index of refraction thereof.

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Preferably said lower cladding layer is made from thermally grown or chemical vapor deposited (CVD) silica, silica containing multicomponent glasses, fluoride glasses, silicon containing organic polymers or silica containing hybrid organic-inorganic polymers or fluorine containing organic

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polymers or fluorine containing hybrid organic-inorganic polymers.

In one preferred embodiment of an integrated optical waveguide interferometer in accordance with the invention said means for raising and lowering the temperature of said polymer cladding material comprises a heater and/or a cooler adjacent to the section of said polymer cladding material. Said heater and/or cooler may include electrical resistive heater stripes or thermo-electric cooling/heating elements that are disposed near said polymer section(s).

In a further preferred embodiment of an integrated optical waveguide interferometer according to the invention said first waveguide core layer and/or said second waveguide core layer is/are provided with a profile in the form of a ridge.

In a further preferred embodiment of an integrated optical waveguide interferometer in accordance with the invention the refractive index of said first waveguide core layer and/or said second waveguide core layer is selected in the range between 1.5 and 2.5. Particularly, said first waveguide core layer and/or said second waveguide core layer is/are at least substantially made from a material selected from the group consisting of Si_3N_4 , TiO_2 , Ta_2O_3 , ZrO_2 , Al_2O_3 , Y_2O_3 and Nb_2O_5 .

In a further preferred embodiment of an integrated optical waveguide interferometer according to the invention a foam is applied on said means for raising and lowering the temperature of said polymer cladding material.

The present interferometer might be sensitive for air

turbulences above the means for raising and lowering the temperature of said polymer cladding material, that is the heaters. These induce interfering signal fluctuations. This can be avoided by applying thin polyurethane (PUR) foam layers as thermal isolators on top of the heaters. PUR foam is an excellent thermal isolator. The foam layer can be applied by dripping a diluted PUR pre-polymer solution onto the heaters and allowing this to cure as a foam layer by moisture uptake from ambient atmosphere. Alternatively, the heaters can be covered with a coverplate of a more dense material, while leaving a narrow, thermally isolating air gap between the surface of the heaters and the coverplate.

In a further preferred embodiment of an integrated optical waveguide interferometer in accordance with this invention means are provided for electrical modulation of a signal of said means for raising and lowering the temperature of said polymer cladding material. An advanced modulation principle, so-called serrodyne modulation, can be used to obtain a sensor response of the present interferometer with high sensitivity. Serrodyne signal processing requires a sinusoidal output signal in order to perform Fourier analysis for optical phase determination. The heater yields primarily a square root modulation in response to an applied voltage. Therefore, a modulation voltage optimized such that a sinusoidal optical modulation is obtained, can be encoded in a lookup table and via a digital/analogue converter send to an electronic circuit. Using diodes, the positive and negative voltages are then routed to separate electrical amplifier circuits which drive the electrical heaters. This way, using a single input modulation signal, derived from a single lookup table, can be used to sequentially drive the heaters of the two thermo-optic modulators of the present

interferometer in order to obtain the sinusoidal optical response, thereby compensating for the non-linear voltage dependent behavior of the thermo-optical effect. Also, the influence of temperature on the resistance of the heaters
5 can be compensated for by a correct design of the lookup table. Instead of two heater elements also one heater element can be provided.

In a further preferred embodiment of an integrated optical
10 waveguide interferometer according to the invention a polarization metal strip is used as said means for raising and lowering the temperature of said polymer cladding material. The present interferometer operates well with one of the two possible light polarization states (TE and TM)
15 only. The optical fiber that inputs the interferometer delivers both polarizations. Therefore a polarization stripper is preferred. This might be done by selective absorption of one of the polarizations (TM) in the Si substrate material in the transport section of the
20 interferometer. This yields an attenuation of < 10 dB/cm. A much higher value (shorter stripper) can be obtained by selective TM mode absorption in a metal layer. In the interferometer this can be the metal layer of the heater. The heater and stripper functionality can be decoupled by
25 applying multilayer metal structures (e.g. Cr/Au with Cr for stripping and Au for heating).

The present invention also relates to the use of an integrated optical waveguide interferometer according to the
30 invention in a dipstick.

The invention will further be elucidated with the help of a drawing relating to a preferred embodiment of an integrated

optical interferometer in accordance with the invention,
wherein

- figure 1 is a schematic layout of a standard integrated
5 optical interferometer of the Mach-Zehnder type;
- figure 2 is a schematic layout of the functioning of
the standard interferometer of figure 1 for evanescent
sensing of chemical and/or physical quantities;
- figure 3 is a schematic layout of the interferometer
10 of figure 2, but now adapted in accordance with the
invention;
- figure 4 relates to a specific use of the
interferometer of figure 3, that is as a dipstick.

15 The interferometer 1 of figure 1 consists of an input
channel waveguide 2 that splits up in two identical branches
3, 4. After a well-defined length, these two branches 3, 4
are combined again to form the output waveguide 5. Light
that enters the input waveguide 2 splits equally over the
20 two branches 3, 4 and combines again at the output waveguide
5. The cross-section of the optical waveguide channel of the
interferometer 1 consists of a high refractive index core
layer with a ridge profile that is sandwiched between low
refractive index buffer layers. In case of buried
25 waveguides, the optical field is completely contained in the
core and buffer layers and the propagation of light is not
affected by environmental disturbances.

With reference to figure 2, by using etching techniques, a
30 top cladding 6 is locally removed above the channel
waveguides at well-defined positions in both branches 3, 4
of the interferometer 1. In these so-called windows 7, 8,
the evanescent field of the light that travels through the

under-laying channel waveguides, extends into the environment above the interferometer 1 and becomes susceptible to environmental changes. An interface layer that binds specifically with analyte molecules of interest is provided on the surface of the sensing window 7. To keep the interferometer 1 balanced, the reference window 8 is provided with an interface layer that shows no specific binding. When sample material is flown over both sensing and reference window 7, 8, specific binding of analyte molecules to the interface layer in the sensing window 7 is probed by the evanescent field of the light travelling through the sensing branch 3. This causes a change of the propagation speed of the light, resulting in a phase difference between light coming from the sensing branch 3 and the reference branch 4 at the output waveguide 5. The induced phase difference is proportional to the amount of analyte molecules binding to the interface layer and results in a periodic change of the light intensity in the output waveguide 5.

With reference to figure 3, by using etching techniques, a top cladding 6 is locally removed above the waveguide channels at well-defined positions in both branches 3,4. These so-called modulation sections are filled with a high refractive index polymer cladding material 9, that is having an index of refraction between 1.46 and 2.5 that varies with temperature. Onto this polymer cladding material 9, a metallic heaterstrip 10 is disposed to change the polymer refractive index upon heating or cooling. This will change the phase of light flowing through the channel to effect modulation of the light in the interferometer. Using an advanced modulation principle (serrodyne modulation) in combination with the thermo-optic active section in the

interferometer 1 and dedicated electronics, the output intensity of the interferometer 1 is transformed into a sensor response signal that is equal to the induced phase difference caused by specific binding of analyte molecules to the interface layer in the sensing window 7.

Figure 4a shows a specific use of the present interferometer shown in figure 3, namely as a dipstick 1 with thermo-optic modulators 11, 12. This interferometer is based on a Mach-Zehnder interferometer having waveguides that are routed back to the input edge of the chip by using a folding mirror 13 or a waveguide bend. As a result, the present interferometer is very compact and is used, as shown, in a dipstick application. In other words, the sensor end may be dipped into a container 14 filled with a (small) quantity of a substance 15 to be analyzed. Figure 4b shows alternative dipstick structures.

CLAIMS

1. Integrated optical waveguide interferometer for evanescent sensing of chemical and/or physical quantities, comprising a substrate carrying a waveguide layer structure provided with
- a first waveguide core layer sandwiched between two first cladding layers formed by a first lower and a first upper cladding layer, of a lower refractive index than the first waveguide core layer,
 - a second waveguide core layer sandwiched between two second claddings layers formed by a second lower and a second upper cladding layer, of a lower refractive index than the second waveguide core layer,
 - a splitter and a combiner for optically coupling said first and second waveguide core layers at first and second junctions, respectively, **characterized by**
 - a modulation section of a polymer cladding material included in one of the first upper cladding layers and/or included in one of the second upper cladding layers, the polymer cladding material covering an identifiable area of said first waveguide core layer and/or said second waveguide core layer between the first and second junctions, said polymer cladding material having an index of refraction between 1.46 and 2.5 that varies with temperature, thereby changing the phase of radiation propagating through said first and second waveguide core layers,
 - means for raising and lowering the temperature of said polymer cladding material.

2. Integrated optical waveguide interferometer according to claim 1, wherein said interferometer in said modulation section satisfies the equations:

$$\begin{aligned} (1) \quad & n_c > n_s \\ (2) \quad & V = 2\pi(h/\lambda)(n_f^2 - n_c^2)^{1/2} \\ (3) \quad & r = (n_f^2 - n_s^2) / (n_f^2 - n_c^2) \end{aligned}$$

with

- n_c being the refractive index of the first upper cladding layer and/or the second upper cladding layer;
- n_s being the refractive index of the first lower cladding layer and/or the second lower cladding layer;
- n_f being the refractive index of the first core layer and/or the second core layer;
- h being the thickness of the first core layer and/or the second core layer;
- λ being the optical wavelength;
- V varying between 0.1 and 4 for $r > 1.1$.

3. Integrated optical waveguide interferometer according to claim 1 or 2, wherein said polymer cladding material is at least substantially made from a material selected from the group consisting of poly pentabromophenyl methacrylate, poly pentabromophenyl acrylate, poly pentabromobenzyl methacrylate, poly pentabromobenzyl acrylate, poly 2,4,6-tribromophenyl methacrylate, polyvinylphenyl sulfide, poly 1-naphthyl methacrylate, poly 2-vinylthiophene, poly 2,6-dichlorostyrene, poly N-vinylphthalamide, poly 2-chlorostyrene en poly pentachlorophenyl methacrylate.

4. Integrated optical waveguide interferometer according to claim 1 or 2, wherein said polymer cladding material is at least substantially made from a material selected from the group consisting of a polymer based on aromatic benzene rings and a polymer based on fused aromatic rings, such as an SU-8 epoxy monomer or an aromatic polyimide.
5. Integrated optical waveguide interferometer according to claim 3 or 4, wherein high refractive index particles have been added to the material of said polymer cladding material in order to increase the index of refraction thereof.
6. Integrated optical waveguide interferometer according to any of the preceding claims 1 through 5, wherein said means for raising and lowering the temperature of said polymer cladding material comprises a heater and/or a cooler adjacent to the section of said polymer cladding material.
7. Integrated optical waveguide interferometer according to any of the preceding claims 1 through 6, wherein said first waveguide core layer and/or said second waveguide core layer is/are provided with a profile in the form of a ridge.
8. Integrated optical waveguide interferometer according to any of the preceding claims 1 through 7, wherein the refractive index of said first waveguide core layer and/or said second waveguide core layer is selected in the range between 1.5 and 2.5.

9. Integrated optical waveguide interferometer according to any of the preceding claims 1 through 8, wherein said first waveguide core layer and/or said second waveguide core layer is/are at least substantially made from a material selected from the group consisting of Si_3N_4 , TiO_2 , Ta_2O_3 , ZrO_2 , Al_2O_3 , Y_2O_3 and Nb_2O_5 .
10. Integrated optical waveguide interferometer according to any of the preceding claims 1 through 9, wherein said first lower cladding layer and/or said second lower cladding layer is/are at least substantially made from thermally grown or chemical vapor deposited (CVD) silica, silica containing multicomponent glasses, fluoride glasses, silicon containing organic polymers or silica containing hybrid organic-inorganic polymers or fluorine containing organic polymers or fluorine containing hybrid organic-inorganic polymers.
11. Integrated optical waveguide interferometer according to any of the preceding claims 1 through 10, wherein a polarizing metal strip is used as said means for raising and lowering the temperature of said polymer cladding material.
12. Integrated optical waveguide interferometer according to any of the preceding claims 1 through 11, wherein a foam is applied on said means for raising and lowering the temperature of said polymer cladding material.
13. Integrated optical waveguide interferometer according to any of the preceding claims 1 through 11, wherein coverplate is applied on said means for raising and

lowering the temperature of said polymer cladding material, and wherein an airgap is maintained between said coverplate and said means for raising and lowering the temperature of said polymer cladding material.

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14. Integrated optical waveguide interferometer according to any of the preceding claims 1 through 13, wherein means are provided for electrical modulation of a signal of said means for raising and lowering the temperature of said polymer cladding material.

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15. Method for electrical modulating a signal of a heater element for raising and lowering the temperature of said polymer cladding material in an integrated optical waveguide interferometer according to any of the preceding claims 1 through 14, wherein the heater is powered with voltages that yield a sinusoidal sensor response of said interferometer for serrodyne signal processing, thereby compensating for the non-linear relation between applied voltage and thermo-optic modulation.

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16. Method according to claim 15, wherein two separate heater elements are provided, and wherein the heater elements are alternately powered with voltages that yield a sinusoidal sensor response of said interferometer for serrodyne signal processing.

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17. Method according to claim 16 wherein a lookup table and an electrical scheme are used, wherein, with help of said electrical scheme, positive and negative voltages are routed from a single input signal to said two separate heater elements, and wherein said lookup table

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is optimized in order to obtain a sinusoidal sensor response of said interferometer for serrodyne signal processing, thereby compensating for the non-linear relation between applied voltage and thermo-optic modulation.

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18. Use of an integrated optical waveguide interferometer according to any of the preceding claims 1 through 14 in a dipstick.