Sensitivity analysis for improving nanomechanical photonic transducers biosensors

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Abstract
The achievement of high sensitivity and highly integrated transducers is one of the main challenges in the development of high-throughput biosensors. The aim of this study is to improve the final sensitivity of an opto-mechanical device to be used as a reliable biosensor. We report the analysis of the mechanical and optical properties of optical waveguide microcantilever transducers, and their dependency on device design and dimensions. The selected layout (geometry) based on two butt-coupled misaligned waveguides displays better sensitivities than an aligned one. With this configuration, we find that an optimal microcantilever thickness range between 150 nm and 400 nm would increase both microcantilever bending during the biorecognition process and increase optical sensitivity to \(4.8 \times 10^{-2} \text{nm}^{-1}\), an order of magnitude higher than other similar opto-mechanical devices. Moreover, the analysis shows that a single mode behaviour of the propagating radiation is required to avoid modal interference that could misinterpret the readout signal.

Keywords: optomechanics, integrated optics devices, biological sensing and sensors

(Some figures may appear in colour only in the online journal)

1. Introduction
The development of transducers to form part of a biosensor device is specifically focused on the achievement of high sensitivity devices for real-time monitoring. These two conditions are fulfilled in the case of nanomechanical transducers, which are becoming valuable sensing platforms for many different applications, ranging from environmental to chemical or biological [1]. The sensitivity of nanomechanical transducers is controlled by several factors such as their mass, damping (energy dissipation), and stiffness. Depending on the method of operation—static or dynamic—different parameters must be optimized. Beside intrinsic transducer sensitivity, the final sensitivity of the biosensor will depend on the readout method of the nanomechanical response. Laser beam reflection, piezoelectric or piezoresistive readout methods are probably the ones most common employed. An alternative method, where a microcantilever forms a waveguide in which light propagates, was presented for the first time by our research group a few years ago [1]. The proposed opto-mechanical device is a combination of the well-known nanomechanical transducer method and integrated optical technology, and was called an optical waveguide microcantilever (OWC). The light propagated through the microcantilever is emitted from the free end, travels across a small gap, and is captured by an output single mode waveguide. Following this initial work, different approaches combining photonic and microcantilever devices have been developed, looking for the higher integration of arrays of microcantilevers with a highly sensitive readout method. Highly integrated opto-mechanical sensors based on silicon [2–4] or polymer technology [5–7] have been presented. However, the sensing applications demonstrated with
this method are still uncommon [8, 9], and the sensitivities achieved are lower than the ones reached with the laser beam reflection method.

In this paper, we present an exhaustive optical and mechanical analysis of photonic microcantilevers in order to improve their sensitivity for use as a biosensor device. Working in the surface stress mode, the rise in sensitivity is achieved by increasing the microcantilever deflection during a sensing process, while reducing the signal to noise ratio. The final sensitivity of the OWC depends on the minimum intensity change that can be detected due to microcantilever deflection. This study shows the analysis of the parameters that have a direct effect on the OWC optical power efficiency and final sensitivity, and determine the optimal values to maximize both the microcantilever deflection and power change. Microcantilever thickness is one of the key parameters studied due to its impact on mechanical and optical behaviors. Other parameters such as the output waveguide thickness and the gap distance, and the dimensions at the interface between the input waveguide and the OWC were also analyzed.

2. Photonic microcantilever transducer method

The OWC working principle is based on the optical coupling efficiency change between two total internal reflection (TIR) butt-coupled waveguides. Figure 1(a) shows a schematic of the device configuration. The first waveguide is a silicon dioxide microcantilever (OWC), and the second one is an output silicon nitride waveguide (OW). Both waveguides are separated by a gap distance, \( L_g \). The light transmitted from the OWC to the OW changes dramatically with the transversal displacement of the OWC free end. This displacement is induced by biomolecular interactions occurring on one side of the OWC (figure 1(c)), given by the surface stress difference between the OWC surfaces. This displacement can be determined by reading the output power changes in the OW using a photodetector. The light reaches the OWC from an input silicon nitride waveguide (IW), where the light is introduced from a laser source using an optical objective.

The microcantilever is vertically displaced with respect to the IW and OW (see figure 1(b)). This configuration has two main effects: (a) the light propagating through the IW is mainly coupled into the OWC by the evanescent field which travels through the silicon oxide cladding; (b) it produces a non-symmetric optical response curve of the OWC with respect to its initial position (zero deflection). With this configuration, and due to the Gaussian profile of the optical response curve, the movement of the microcantilever during the biorecognition process will take place in a high sensitivity region of the optical response curve, also sensing the direction (up or down) of the OWC deflection.

2.1. OWC design

The OWC device is a silicon dioxide microcantilever, with length, \( L_c \), thickness, \( h_c \), and width, \( b_c \), which acts as the core of a rectangular waveguide where the light is confined, and where the external medium acts as the cladding (see figure 1(b)).

The IW and OW have a rectangular silicon nitride core, surrounded by silicon dioxide cladding, which make a symmetric waveguide. Both cores have the same dimensions: thickness, \( h_w \), and width, \( b_w \). The IW and OW have an important role in the total device optical power efficiency and device sensitivity.

The end of the IW and the clamped side of the OWC are separated horizontally by a protection distance, \( L_s \). This protection distance avoids additional extra stress in the microcantilever clamp due to the silicon oxide–silicon nitride interface and the gradient stress that could be generated by the deposition of the silicon nitride layer. The \( L_s \) distance must be optimized to achieve the maximum coupling of light between the IW and the OWC, and, therefore, to maximize the optical power efficiency.

The OW is separated from the free end of the OWC by a gap of a few microns, distance \( L_g \). The gap distance has a direct effect on the optical sensitivity and the maximum deflection amplitude that the OW can read.

In order to increase sensitivity and optical power efficiency we have studied how each of the above dimensions affects the OWC behavior. The main aim is to increase the mechanical deflection and to maximize the output power change in relation to mechanical bending.
2.2. Theory and modelling

During a biosensing assay, biomolecular interactions occur on one side of the OWC and a differential surface stress, \( \Delta \sigma \), between the two OWC surfaces is produced, inducing the displacement, \( \Delta y \), of the OWC free end. The deflection distance \( \Delta y \) can be approximated by the Stoney equation, including the effect of clamping [10]:

\[
\Delta y \approx \frac{3K(1-\nu)}{E} \left( \frac{L_c}{h_c} \right)^2 \Delta \sigma
\]  

where \( \nu \) is the Poisson ratio, \( E \) is the Young modulus, \( K \) is a constant dependent on the material and geometrical properties of the microcantilever, and \( L_c \) and \( h_c \) are the length and the thickness of the microcantilever, respectively. Working in the static mode, the minimum deflection that could be detected would also depend on the microcantilever thermal noise (Brownian motion). The microcantilever dimensions must be chosen in order to achieve a high signal to noise ratio. The microcantilever vibration is characterized by its resonance frequency for a specific vibration mode, \( w_n \), and its quality factor, \( Q_n \). The thermal noise amplitude, \( \Delta y_{\text{min}} \), can be obtained from equation (2), derived from the equipartition theorem, where the average energy of a system in thermal equilibrium is the same for each vibration mode:

\[
\Delta y_{\text{min}} = \frac{2k_B T \Delta w}{\pi Q_n k w_n}
\]  

where \( k_B \) is the Boltzmann constant, \( T \) is the temperature, \( \Delta w \) is the bandwidth and \( k \) is the microcantilever spring constant. The resonance frequency derived from the Euler–Bernoulli beam theory [11] is given by [12]:

\[
w_n \approx \frac{\alpha_n}{\pi} \frac{h_c}{L_c^2} \sqrt{\frac{E}{12\rho_c}}
\]  

where \( \rho_c \) is the microcantilever density and \( \alpha_n \) takes values of 1.875, 4.694, 7.588 for the first three vibration modes [13].

Finally the \( Q \) factor for each vibration mode can be obtained from the Hosaka \textit{et al} approximation, where the microcantilever is modeled as a line of spheres with diameter \( b \) equal to the microcantilever width, surrounded by an external medium with density, \( \rho_{\text{env}} \), and viscosity, \( \nu \) [14]:

\[
Q_n = \frac{\rho_c h_c b^3 w_n}{3\pi \eta b + \frac{3}{2} \pi b^2 b \sqrt{2/\rho_{\text{env}}} w_n}
\]  

The proposed opto-mechanical device is at the same time based on dielectric waveguides, where the light is confined by the total internal reflection (TIR) into a medium with a high refractive index (the core), surrounded by mediums of lower index (the cladding). According to the Maxwell theory, light can propagate in such a structure in the form of guided modes, characterized by their effective refractive index. For a transversal electric polarization (TE), the solution of the wave equation depends on the wavelength, the refractive index of the core and cladding, and the propagation constant. By applying the boundary conditions \( y \rightarrow \pm \infty \), and by imposing the continuity of \( E_y \) and \( \partial E_y / \partial x \) at the interfaces, we can obtain the eigenvalue equation for the TE modes for asymmetric planar waveguides:

\[
V \sqrt{1-b} = m\pi + \tan^{-1} \left( \frac{b}{1-b} \right) + \tan^{-1} \left( \frac{b+a}{1-b} \right)
\]  

where \( b \) is the normalized effective refractive index, \( V \) is the normalized thickness of the waveguide, and \( a \) is the asymmetry of the slab waveguide. From equation (5) it is possible to calculate the \( E_y \) component of the electric field in each region of the slab waveguide:

\[
E_y(y) = \begin{cases} 
A \left( \cos(k_n d) + \frac{\gamma_n}{k_n} \sin(k_n d) \right) e^{-\gamma_n y} & y > d \\
A \left( \cos(k_m y) + \frac{\gamma_m}{k_m} \sin(k_m y) \right) & 0 < y < d \\
A e^{-\gamma_n y} & y \leq 0 
\end{cases}
\]  

where \( k_n, \gamma_n \), and \( \rho_n \) are the transverse propagation coefficients for the core, cladding and substrate, respectively and \( d \) is the core thickness. The electric field shows a sinusoidal dependence in the core and exponentially decreases in the cladding (evanescent field). The constant \( A \) represents the field amplitude, and is related to the energy carried by the mode.

When a specific mode changes from one waveguide to another, the coupling coefficient for each mode into the second waveguide can be obtained by the overlapping integral [15]:

\[
\eta = \frac{\left( \int_{-\infty}^{\infty} A_n(y) B_m^*(y) dy \right)^2}{\int_{-\infty}^{\infty} A_n(y) A_n^*(y) dy \int_{-\infty}^{\infty} B_m(y) B_m^*(y) dy}
\]  

where \( A_n \) is the amplitude distribution of the mode \( n \) in the first waveguide, and \( B_m \) is the amplitude distribution of the mode \( m \) in the second waveguide.

2.3. OWC sensitivity

The final sensitivity of the OWC device is the combination of the mechanical and optical sensitivity. The interrelation of the different OWC parameters that affect both sensitivity and the optical power efficiency is shown in figure 2.

The mechanical sensitivity is related to the OWC free end deflection when the biomolecular interactions occur on its surface. This sensitivity depends on the material and dimensions of the OWC, as can be observed in the Stoney equation. According to this model, beside the material properties, the main physical parameters that govern the mechanical response are the OWC length, \( L_c \), and thickness, \( h_c \). Higher microcantilever deflections would be achieved for longer and thinner microcantilevers.

The optical sensitivity, \( S \), is defined as the optical power efficiency, \( \eta \), and changes between the OWC and the OW per unit of microcantilever displacement:

\[
S = \frac{\partial \eta}{\partial z}
\]
Thus, the optical sensitivity depends on the OWC and OW dimensions. As shown in figure 2, the OWC thickness is the critical dimension of the device because it affects both the mechanical and optical sensitivities. Finally, with regard to the total optical power efficiency, the distance between the IW and OWC must also be considered.

3. Numerical analysis

Numerical simulations in COMSOL multiphysics [16] were done to obtain the optimal device dimensions. We studied how each dimension affects the OWC behavior to maximize the mechanical deflection and also to find the maximum optical output power changes in relation to mechanical bending.

To verify the initial results for the optical and mechanical equations, analytical calculations were done using python scripts with SciPy libraries [17], which helped us to compare the analytical results with the COMSOL simulations.

The material selected for the microcantilever is silicon dioxide (SiO$_2$) with a refractive index of $n_{SiO_2} = 1.46$, Young’s modulus $E = 70 \times 10^9$ Pa and Poisson’s ratio of $\nu = 0.17$. The microcantilever acts like a symmetric waveguide, where the surrounding medium, air ($n_{air} = 1$) or water ($n_{water} = 1.33$), acts like cladding. The material selected for the IW and the OW core is silicon nitride, with a refractive index of $n_{SiN_2} = 2.00$. The material selected for the surrounding cladding layers is silicon dioxide with a refractive index of $n_{SiO_2} = 1.46$.

The simulations were executed by a computer with a 4 core processor (Intel Xeon E5520) working at 2.27 GHz frequency and 24 GB RAM memory, running a Windows 2008 server operating system.

4. Results and discussion

4.1. OWC mechanical behavior

A simulation of the relationship between the microcantilever free end bending and the microcantilever thickness for lengths between 100$\mu$m and 500$\mu$m of length, for a differential surface stress of $\Delta \sigma = 0.05$ N m$^{-1}$.

The physical model employed is shown in figure 3(a). A silicon dioxide rectangular beam, with dimensions $L_x$, $h_c$ and $b$, is clamped to a fixed block of the same material. A homogeneous rectangular mesh was selected for the microcantilever domain and a tetrahedral mesh for the fixed block, which reduced the processing time.
The proposed design has three waveguides: two identical silicon nitride core waveguides (IW and OW), and a silicon dioxide microcantilever (OWC). The number of guided modes that will propagate along these waveguides is determined by the relation of the effective refractive index, \( N_{\text{eff}} \), of each waveguide to its thickness.

We considered the waveguides as symmetric slabs, because of the high relation between the width and thickness. The physical model consists of a slab waveguide section, with an input \( x = 0 \), where the electric field profile \( E_y(x) \) is calculated for a TE polarization. For optical simulations, the mesh size must be at least \( \lambda/3 \). We chose to use a mesh with a rectangular distribution in the core, and a triangular distribution for the cladding layers, for \( \lambda = 660 \) nm. Solving the dispersion equation (5) for the TE modes, the effective refractive index for each propagation mode, \( m \), as a function of the waveguide thickness was obtained. The effective refractive index for the input and output waveguides is shown in figure 4(a). For the OWC we analyzed two different conditions: when the microcantilever is surrounded by air (\( n_{\text{air}} = 1 \)) and by water (\( n_{\text{water}} = 1.33 \)), shown in figures 4(b) and (c), respectively. In both cases, the number of propagation modes increased with the thickness of the waveguide.

The theoretical cut-off for the single mode behavior for TE modes can be derived by making \( N_{\text{eff}} \) equal to the substrate refractive index \( (n_i) \) for each case, so \( b \to 0 \). Operating with the dispersion equation (5), the value of the cut-off thickness for the number of \( m \) modes that can propagate can be written as:

\[
V_{\text{TE}} = mx + \tan^{-1}\sqrt{a}
\]

(9)

As the three waveguides are symmetric, the fundamental mode always exists, thus the maximum thickness for a single mode behavior is \( h_w = 241.42 \) nm for IW and OW, and \( h_c = 310.22 \) nm and \( h_c = 554.09 \) nm for the OWC in air and water, respectively.

4.3. Optical models

The optical propagation in the device was analyzed in two steps. Initially, a physical model including only the IW–OWC (see figure 5(a)) interface was considered, with the aim of finding the values that maximize their optical coupling efficiency. Next, the OW was included, to simulate the behavior of the whole device (see figure 5(b)).

In both cases, the physical model is surrounded by artificial regions called perfect matching layers (PMLs). The aim of these regions is to absorb the electromagnetic field at the boundaries to avoid reflections, allowing the reduction of the dimensions of the simulation model and saving calculation time. The meshing strategy is based on rectangular elements in the IW, OW and OWC with a maximum element size of 41.25 nm (\( \lambda/16 \)).

The optical power efficiency, \( \eta \), of the device is defined as the ratio between the introduced optical power and output power. Considering a TE fundamental mode as the input light source, with 1.0 W power, the optical power efficiency can be obtained as:

\[
\eta = 10^{\frac{S_{21}[\text{dB}]}{10}}
\]

(10)

where \( S_{21} \) is the scatter parameter that relates the output power to the input power.

4.4. IW and OWC interface

The light from the IW is coupled into the OWC at the microcantilever clamping region. To keep the fabrication process as simple as possible, the IW has a rectangular shape (figure 5(a)). This interface between the IW and the OWC has a critical influence on the device output optical power and it has an impact on the signal to noise ratio.

To improve the overall optical power efficiency, we studied the output power at the free end of the OWC for three different IW thicknesses (80 nm, 130 nm and 180 nm) and an OWC thickness range from 100 nm to 1 \( \mu \)m.

The results of this study, for air and water as external mediums, are shown in figures 6(a) and (b), respectively, where the coupling efficiency of each propagation mode is calculated for each OWC thickness. The coupling efficiency increase for smaller IW thicknesses is due to a deeper penetration of the evanescent field of the fundamental mode as the IW thickness is reduced. With regard to the OWC thickness, the maximum coupling efficiency occurs when the OWC has a single mode behavior. For an OWC thickness higher than

| OWC thickness \((h_c)\) | Resonance frequency \([\text{kHz}]\) | Microcantilever bending \([\text{nm}]\) |
|-----------------|-----------------|-----------------|
|                 | Analytical      | Simulation      | Analytical | Simulation      |
| 250 nm          | 22.78           | 22.86           | 296.80     | 294.08          |
| 350 nm          | 31.89           | 32.02           | 151.43     | 150.03          |
| 500 nm          | 45.56           | 45.71           | 74.20      | 73.50           |
Figure 4. Dependency of the effective refractive index of each waveguide as a function of the thickness: (a) IW and OW, (b) OWC in air, and (c) OWC in water.

Figure 5. Physical models used for COMSOL simulations: (a) model used in the study of the IW and OWC interface to increase the optical coupling efficiency into the OWC, and (b) model used in the study of device sensitivity and device optical power efficiency.

Figure 6. IW-OWC interface coupling efficiency as a function of microcantilever thickness for a specific external medium, (a) coupling efficiency for air as external medium, and (b) coupling efficiency for water as external medium.
the cut-off thickness, the power is split between the propagation modes, which decreases the coupling efficiency of the fundamental mode, generating a more complex response, as shown in section 4.7. Therefore, the maximum coupling efficiency of the fundamental mode occurs for an OWC thickness of around 200 nm in water (figure 6(b)), and this cut-off thickness is under 100 nm when surrounded by air (figure 6(a)). The electric field representation for water as external medium is shown in the insets of figure 6(b), where higher light coupling is observed only when the fundamental mode is guided (inset on the left). In the case of two guided modes, it is possible to observe the interference between both propagation modes along the microcantilever (inset on the right), producing a spatial displacement of the output response at the microcantilever free end.

4.5. IW–OWC interface (safety distance)

Another parameter that could affect the light coupling between the IW and the OWC is the distance between the IW end and the microcantilever clamp. This distance of only a few nanometers is called the security distance, \( L_s \) (figure 5(a)). From a fabrication point of view, the security distance has a positive effect, because it reduces the possible stress induced in the fabrication process, leaving the OWC free of initial stress. We used the previous physical model to study the effect of the safety distance (figure 5(a)).

The result when water is the external medium is shown in figure 7, where the relation between coupling efficiency and \( L_s \) is obtained for an IW 130 nm thick. We can observe that for microcantilevers thicker than 200 nm, the coupling efficiency of the fundamental mode is slightly improved for \( L_s = 0.5 \mu m \) (with respect to \( L_s = 0 \mu m \)).

For larger \( L_s \), the coupling efficiency has a lower dependence on the OWC thickness, due to a change in the power transmission mechanics during light coupling. For smaller \( L_s \), the light is mainly coupled through the evanescent field, while for large distances, direct coupling is the principal mechanism. The same effect occurred with air as the external medium. In order to achieve an increase of the optical power efficiency for OWC with a single mode behavior, the optimal \( L_s \) distance selected was 0.5 \( \mu m \).

4.6. Gap effect—static response

The OWC free end is separated from the OW by a few nanometers, called the gap distance (\( L_g \)). This distance has a strong influence on OWC sensitivity and on the maximum detectable bending range. To exploit the final sensitivity of the device, we performed a static analysis, including the influence of the OWC thickness on optical power efficiency for two different gap distances and two waveguide thicknesses. The physical model employed included all of the elements IW, OWC and OW (figure 5(b)), with an initial position of zero deflection for the OWC. For simplicity in the fabrication process, the OW and IW have the same thickness, are single mode, and both are protected by a 1 \( \mu m \) silicon dioxide layer to avoid propagation losses due to light scattering.

The relation between the optical power efficiency at the end of the OW as a function of the OWC thickness for gap distances \( L_g = 1 \mu m \) and \( L_g = 2 \mu m \) is plotted in figure 8. The efficiency is obtained from equation (10), using the previously calculated scatter parameter \( S_{zz} \) for the fundamental mode at the end of the OW. Water is considered as the external medium, with an IW and OW thicknesses of 130 nm and 180 nm, respectively. The modal behavior as function of the OWC thickness is clear for both \( L_g \) distances. For an OWC thickness lower than 500 nm the single mode behavior has a maximum efficiency zone in the range of 175 nm up to 300 nm, with a maximal efficiency of around 25% for a 130 nm waveguide with an \( L_g = 1 \mu m \). For waveguide thicknesses of 180 nm, the efficiency is around 20%, both for \( L_g = 1 \mu m \) and \( L_g = 2 \mu m \), given that the increased \( L_g \) distance is compensated by the higher OW thickness.

For an OWC thickness higher than 500 nm, the multimode behavior creates constructive and destructive zones that affect the output power. This effect is undesirable because any change in the refractive index of the external medium will be translated into a variation of the effective refractive index of the propagating mode, which could hide or modify any change in the optical power due to a biorecognition process. This effect is discussed more in detail in section 4.8.

4.7. Effect of cantilever thickness on the free-end displacement

The OWC bending response, and the change of light power coupled into the OW during its deflection, determines the device sensitivity. Trying to obtain a realistic behavior of the device, we used the same physical model (figure 5(b)), combining the physics of solid mechanics and the electromagnetic waves in COMSOL.

We studied the change in the optical power efficiency when a force is applied at the end of the OW, mimicking a change of the surface stress of the microcantilever. After the OW is bent, a COMSOL frequency study is applied to calculate the light propagation in the device during the OWC deflection. Varying the applied force, the relationship
between the displacement of the free end and the optical power efficiency was obtained. Figures 9(a) and (b) show the optical power efficiency for the corresponding OWC bending for different microcantilever thicknesses and gap distances of 1 μm and 2 μm, respectively. Directly applying the derivative of these curves, the device sensitivity was obtained in figures 9(c) and (d).

The sensitivity of an OWC thickness of 350 nm, with 1 μm of gap distance is 4.8 × 10^-2 nm^-1. This sensitivity is an order of magnitude higher than other opto-mechanical

**Figure 8.** Optical power efficiency: (a) gap distance of 1 μm, and (b) gap distance of 2 μm.

**Figure 9.** OWC bending response for: (a) Lg = 1 μm, and (b) Lg = 2 μm. OWC sensitivity for: (c) Lg = 1 μm, and (d) Lg = 2 μm.

**Table 2.** Optical initial efficiency and OWC deflection for 3 dB coupling losses, IW and OW thickness 130 nm, water as external medium.

| OWC thickness (hc) | Initial efficiency | 3 dB displacement |
|--------------------|-------------------|-------------------|
| Lg = 1 μm          | Lg = 2 μm         | Lg = 1 μm         | Lg = 2 μm         |
|-------------------|-------------------|-------------------|-------------------|
| 250 nm            | 0.258             | 0.203             | 252 nm            | 381 nm            |
| 350 nm            | 0.197             | 0.168             | 188 nm            | 297 nm            |
| 500 nm            | 0.102             | 0.084             | 114 nm            | 221 nm            |
The reason for this increase of sensitivity is due to the optimal OWC thickness which confines the propagation mode, along with the misalignment between the OWC and OW for zero OWC displacement (figures 9(c) and (d)). Any change of power due to microcantilever bending occurs in the region of the maximum slope of the optical response and, therefore, will exhibit better sensitivities than if they were perfectly aligned, in spite of the decrease in the optical power efficiency. Figures 9(a) and (b) also show the effect of the gap distances. Gap distances of 1 μm show narrower Gaussian profiles of the optical power efficiency than gaps of 2 μm. In contrast, the microcantilever deflection range that could be measured decreases with the shorter gaps. For that reason, the selection of the gap distance is a compromise between the sensitivity and the maximal measurable OWC deflection.

Table 2 shows the microcantilever deflection that would be necessary to produce a 3 dB change of optical power efficiency for each gap distance. The deflections were calculated for devices with IW and OW thicknesses of 130 nm and with water as the external medium. For an OWC with a thickness of 350 nm, the 2 μm gap distance required nearly double the deflection to produce the same change for gaps of 1 μm.

4.8. Refractive index effect

The biorecognition process involves changes in the OWC environment due to changes in the solution where the biomolecules are transported. As the external medium acts as OWC cladding, this influences the effective refractive index of the guided modes. For an OWC with a multimode behavior, changes in the external refractive index generate interferences between each propagation mode and, in consequence, in the output power.

To study this influence, we simulated the effect of a refractive index change of the external medium of 6 × 10²⁻² RIU for three different OWC thicknesses: 250 nm, 550 nm and 700 nm. Changes in the optical power efficiency are related to the phase change of a sinusoidal signal, and depend on the working wavelength, \( \lambda \), the difference between the effective index of the two guided modes, \( \Delta N_{\text{eff}} \), and the OWC length, \( L_c \) [20]:

\[
\Delta \theta = 2\pi \frac{L_c}{\lambda} \Delta N_{\text{eff}}
\]

Two different behaviors of optical power efficiency can be observed with the external refractive index change (figure 10(a)): for a multimode OWC (\( h_c > 500 \) nm) the mode interference produces an oscillation in the efficiency of about 30%. Instead, for a single-mode OWC the variation is less than 5%. For this reason an OWC with a single mode behavior is preferred, avoiding displacement readouts that could hide or affect the signal produced by the biorecognition process. Similarly, an OWC with a bimodal behavior can shift the maximum peak position depending on the external medium, due to the effect of the external medium on the effective refractive index of the guided modes, as shown in figure 10(b).

Fortunately, the changes in the refractive index of the medium due to the presence of molecules are much lower than in the case shown here. The injection of a specific solution with different concentrations of molecules should not have any effect on the device’s modal behavior.

4.9. Figure of merit

Finally, to characterize the performance of the device relative to its optical power efficiency and sensitivity, we defined the figure of merit (FOM) as:

\[
\text{FOM} = \eta \frac{\partial n}{\partial z}
\]

The FOM value for two waveguide thicknesses, \( h_w = 130 \) nm and \( h_w = 180 \) nm, and for gap distances \( L_g = 1 \) μm and \( L_g = 2 \) μm, is shown in figure 11. In all cases a microcantilever thickness range between 150 nm up to 400 nm meets with the best optical power efficiency response with a high sensitivity.
5. Conclusions

We have analyzed the main parameters that affect the final performance of OWC devices to be employed as reliable biosensors in order to improve their surface stress sensitivity and maximize their optical response. We have studied both the mechanical and the optical response for different waveguides and microcantilever thicknesses, external mediums and gap distances. We conclude that an OWC thickness in the range of 150–400 nm produces an increment of sensitivity, with a maximum sensitivity of $4.8 \times 10^{-2}$ nm$^{-1}$, for a 350 nm thickness, an order of magnitude higher than other similar optomechanical devices. This increase of sensitivity is motivated by a high optical response because of its single mode behavior and the misalignment between the OWC and the output waveguide. Besides OWC thickness, gap distances of 1 $\mu$m and 2 $\mu$m between the OWC and the output waveguide were analyzed in order to obtain the relation between the output power changes with the free end OWC movement and the maximum detectable deflection distance. To maximize the total optical output power, the OWC and input waveguide interface was studied, and the distance between both has a high impact on the output power; 500 nm was selected as an optimum distance to maximize the device output signal and, therefore, its signal to noise ratio.

Biomolecular interactions can generate refractive index changes on the transducer surface, for this reason the device response to the refractive index changes of the external medium has been analyzed for the selected dimensions. Despite a clear dependence of the optical response on the changes of the refractive index, the optical power variation is lower than 5% for a single mode OWC, and 30% for a multimode OWC, due to modal interferences.

In order to select the optimal dimensions that generate the maximum sensitivity and maximum output power, a figure of merit has been used. These dimensions will be taken into account in the design of the subsequent fabrication process in our clean room facilities, in order to obtain devices that will be used as opto-nanomechanical transducers for surface stress biosensors of high sensitivity.

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