Analysis of ARROW Waveguide Based Microcantilever for Sensing Application

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Abstract
Analysis of microcantilever beam and anti-resonant reflecting optical waveguide (ARROW) microcantilever waveguides are presented in this work. The silicon nitride material is used to generate microcantilever beams in which varying electric voltage is applied to create the deformation and thus leads to displacement of the beam due to bending of the cantilever tip. Thereby, an integration of micro electro mechanical systems (MEMS) cantilever and ARROW waveguide produced a new ARROW microcantilever waveguide reasonable for obtaining a high quality factor, electric field intensity and sensitivity. These parameters are analyzed by varying the air gap distance between cantilever waveguide and output waveguide. Especially, maximum finite-difference time-domain (FDTD) sensitivity is reached to 73.78 nm/RIU for the proposed ARROW microcantilever waveguide.

Keywords Microcantilever · 2.5D FDTD · Quality factor · Sensitivity · ARROW waveguide

1 Introduction

Microcantilever devices are used for sensing application. The cantilever array biosensor designed has capability of detecting analyte sample. The design was developed mainly to improve the sensitivity of the cantilever-based sensor [1]. The material such as silicon [2], silicon nitride [3] and polymer materials are used for simulating and fabricating the cantilever. The mechanical property of the cantilever designed is very important. M-test was conducted to measure the mechanical property. The mathematical modeling tools such as finite difference, finite element method and energy method are used for the simulation [2].

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Atomic force microscope (AFM) has microcantilever device in its architecture. The beam immersed in viscous fluid has a response. The measurement of the frequency response for the designed cantilever has application in atomic force microscopy [4]. The cantilever mainly used in AFM and excitation of the tip of cantilever using electrical signal is discussed. The sample surface topography can be scanned using multiple cantilever [5]. Another application of the cantilever is in optical waveguide. Nano mechanical transduces that has mechanical and optical models. The sensor developed has sensitivity of $5.7 \times 10^{-4}$ nm$^{-1}$. The modelling method involved in the design was finite element method (FEM) [6]. Nanomechanical sensor also used for detection of femtogram mass using photo thermal actuation. A gold coated nano mechanical cantilever is used with frequency range from 1 to 10 MHz [7].

Certain cantilever is used in environmental application as a sensor. The thermal sensors and humidity sensors are the example. The piezoresistive read out based integrated device was modelled. The model is promising tool for sensing application in liquid environment [8]. MEMS cantilever device are popular structure and they are used as a resonator. These structures are of small size, energy consumption is less and durable. The silicon based microcantilever has quality factor of 35 [9]. The electrostatically actuated device with deflection model is modeled and simulated using MEMS [10].

Gallium nitride microcantilever with vanadium oxide material used as thermal sensor. The variation of the temperature of cantilever device result in the sensitivity change and is used in sensing application [11]. The vanadium oxide is the piezoresistive material used in the sensor. The cantilever designed using polymer material, which has length greater than that of the width [12]. The shape of the cantilever varies from one application to other; the T shaped cantilever device is used as sensor. The analyte used for the experimental purpose was DNA chains [13]. The shapes of the cantilever are T-shape cantilever, slotted cantilever, paddle cantilever and triangular cantilever. The variation of the slot gives variation in the frequency value and quality factor value. Based on the gap length of waveguide from 0 to 40 µm there is change in the quality factor from 0 to 800 [3].

The flow sensor cantilever waveguide is designed using polydimethylsiloxane (PDMS) material. The deflection of the cantilever was analyzed with experimental values [14]. The complete flow sensor with integrated microchannel and detection system is simulated. The software used in the simulation process is COMSOL Multiphysics [15]. PDMS polymer is very versatile material for microfabrication because of its properties for the medical application. The properties are biocompatibility of the material with other analyte sample and the chemical sample used in the modeling and transparency of the material. Array of cantilever beams are used imaging application in AFM. A non-linear system is developed for the scanning that has application in AFM such as cutting, pushing and lithography [16]. The laser bending of the cantilever waveguide was fabricated using silicon material. The main purpose is for parallel sensing of the position. The dimension of the device reported was $110 \times 13 \times 0.6$ µm respectively length width and thickness of the cantilever [17].

A chemical sensor using MEMS concept and position sensitive detector (PSD) are designed using the piezoelectric material for sensing purpose. Also simulated the multilayer cantilever device [18]. Chemical vapor deposition (CVD) is used in the fabrication of the optical waveguide cantilever sensor. The two important CVD methods are low pressure CVD (LPCVD) and plasma enhanced CVD (PECVD). The beam propagation method (BPM) was the mathematical modeling method used to find the nanomechanical forces in the cantilever [19]. The fabricated silicon dioxide on silicon substrate based optical waveguide cantilever has actuated by light. This article shows that there is an exponential decay in the power output for applied power input at the cantilever structure. [20]. The design
consideration discussed are dynamic analysis of the cantilever, lumped model analysis and stability analysis [21]. These electrostatically actuated microcantilever used as a bio mass sensor. These micro structures attached with the carbon nano tube (CNT). The single walled CNT as a sensor was explored [22].

The microcantilever sensor are also used detection of the variation in the pH values in the chemicals. The material used for designing are silicon nitride and silicon dioxide [23]. In electro mechanical device the calibration is very important. Reliable calibration is the main concentration in the Mishra et.al. paper. equipartition theorem and AFM are used for the purpose of calibration [24]. The microcantilever structure with grating is fabricated using two materials in the mid-IR range (3–11 µm) to overcome the spectral bandwidth issues problem. The model enhances the sensitivity and transmission [25]. The micro milling and molding methods were used for the fabrication of the microcantilever beam [26]. The cantilever biosensor based on the adsorption method was reported. Proteins samples adsorption process on the functionalized cantilever surface results in the bend in the cantilever [27]. The analysis of nonlinear modes when the cantilever excitation was done using the invariant techniques with amplitude vibration [28]. The main concept used in major design and analysis of the cantilever is the optical readout method. The single mode waveguides are suitable for the optical read out method. The sensitivity of the sensor with air and liquid both discussed [29].

In this paper, analysis of microcantilever beam and anti-resonant reflecting optical waveguide (ARROW) microcantilever waveguides are presented. The silicon nitride material is used to generate different length, width and thickness (300 × 40 × 20) µm by applying finite element method. The electrostatic voltage is passed to the electrodes present in the insulated chamber. The proposed ARROW microcantilever waveguide produced reasonable results for obtaining a high quality factor, electric filed intensity and sensitivity. Additionally, these parameters are analyzed by varying the air gap distance between cantilever waveguide and output waveguide.

The first section is the introduction to the cantilever based micro nano devices. Second section is modeling of cantilever beam and reflecting optical waveguide (ARROW) microcantilever structure. The materials used for both the structure designing is discussed. The mechanical and optical modeling of the cantilever is explained. The section three is mainly the highlights on the results obtained for cantilever beam and ARROW microcantilever waveguide. The quality factor is also discussed. The section four is discussion on the electric filed intensity modeling of the ARROW cantilever and also on the sensitivity analysis of the ARROW microcantilever waveguide.

2 Design of Cantilever Beam and Cantilever ARROW Waveguide

In this section we discuss the cantilever beam and anti-resonant reflecting optical waveguide (ARROW) cantilever structure. The ARROW devices are single mode, low loss and a good light confinement device used in sensing application [30]. The optical life confinement of the ARROW waveguide using 2.5D FDTD method is discussed. The ARROW waveguide used is B type where in the core and second cladding refractive are greater than that of the first cladding. This design is advantageous compared to the conventional or ARROW-A type waveguide. The ARROW device has two variation namely, hollow core ARROW and liquid core ARROW. In this section we discuss the modeling of the
cantilever beam and ARROW-B cantilever waveguide. Further in discussion ARROW-B waveguide is simply denoted as ARROW waveguide.

2.1 Modeling of Microcantilever Beam

The cantilever has mechanical characteristics such as radius, stress, force, strain and momentum etc. The sensitivity of the microcantilever varies depending on the Poisson’s ratio and Young’s modulus. The basic characteristics of the cantilever are given below. The stress ($\sigma$) is represented in Eq. (1).

$$\sigma = \frac{F}{A}$$  \hspace{1cm} (1)

The strain ($\varepsilon$) is given in Eq. (2)

$$\varepsilon = \frac{\Delta L}{L}$$  \hspace{1cm} (2)

Young’s modulus (E) is the stiffness of the material is given by Eq. (3).

$$E = \frac{\sigma}{\varepsilon}$$  \hspace{1cm} (3)

Here F is the force applied and A is the area of cross section of the cantilever. $\Delta L$ is the change in the length and Length of the cantilever is L. The micro cantilever beam is shown in Fig. 1. The cantilever has 300 µm length, width 20 µm and thickness is 2 µm. The beam is firmly fixed at one side of cantilever and it freely moves at the other side of the cantilever.

The 2D view of the cantilever is shown in Fig. 2. The beam is located in the air-filled cabin. The geometry of the cantilever in the YZ plane is depicted. The insulated chamber is electrically isolated and electrode is grounded. The shown cantilever is fixed at x = 0. and has dimension of 300 × 40 × 20 length, width and thickness respectively.

The common material used for MEMS based devices are silicon nitride and silicon material. The silicon nitride material property and dimension as shown in Table 1. The Young’s modulus is quantity that shows the material with stand capability. It is also

Fig. 1  Microcantilever beam
represented in terms of stress and strain. The Poisson’s ratio of the material depends on the Poisson effect. In Poisson phenomenon, the material has tendency to extend in the direction perpendicular to its direction path. The density of the silicon nitride is mass per unit volume. The pressure and temperature change the material property of silicon nitride material.

The Fig. 3 shows the rectangular meshing used in the design. This is the simple meshing method to find the solution by dividing the geometry into smaller areas. Finite element method uses meshing concept to decrease the degree of freedom.
2.2 Microcantilever ARROW Waveguide

In this section we discuss the mechanical modeling of the cantilever waveguide. The concept of ARROW waveguide and its concepts in the cantilever waveguide and optical modeling of the cantilever waveguide.

2.2.1 Mechanical Model

The bending of the cantilever is characterized by the functional area. The interaction of the molecules on the surface of the cantilever waveguide leads to surface stress $\Delta \delta$, this intern leads to deflection in the waveguide and is given in the Eq. (4) [6].

$$\Delta y \approx \frac{3k(1-\nu)}{E} \left(\frac{l_c}{t_c}\right)^2 \Delta \delta$$

In above Eq. (4), $k$ is constant depends on waveguide geometry and material. $\nu$ is the Poisson ratio, $l_c$ length of the cantilever, $t_c$ is the thickness of the cantilever and $E$ is Young modulus.

2.2.2 Concept of ARROW Waveguide

The ARROW B waveguide is incorporated in the simulation of the ARROW B microcantilever waveguide.

The ARROW waveguide is a five-layer device as shown in Fig. 4. The ARROW-B microcantilever has four regions of operation namely input waveguide region, second is cantilever waveguide, third region is the air gap and fourth region is the output waveguide. The selection of the dimension of the device is very important in the ARROW waveguide design. The selection was thickness of each layer is by considering the below Eqs. (5) and (6). The first cladding layer thickness $(t_1)$ is given by the below Eq. (5) [30]

$$t_1 = \frac{\lambda}{4n_i} \left[ 1 - \left( \frac{n_c}{n_1} \right)^2 + \left( \frac{\lambda}{2\eta_t t_c} \right)^2 \left( 2N + 1 \right)^{-1/2} \right]$$

The second cladding layer has thickness $(t_2)$ half of the core thickness given in Eq. (6)

Fig. 4 Microcantilever ARROW device

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The refractive index values for the ARROW-B microcantilever waveguide are tabulated in Table 2. Each layer material used and RI is given. A bulk silicon substrate is considered, above which a 2 µm silicon nitride second cladding layer is deposited. A silicon dioxide layer of 0.12 µm is fabricated and above the silicon dioxide layer we have a 4 µm silicon nitride layer is deposited. This completes the structure of ARROW microcantilever waveguide. The length, width and thickness of the structure is 40 x 10 x 10 respectively.

The ARROW waveguide XY, XZ, YZ and complete view is shown in Fig. 5. The modal analysis carried for the ARROW -B microcantilever waveguide. The first cladding layer thickness is very small. The second cladding thickness is half of the core thickness. The

\[ t_2 = \frac{t_c}{2} (2m + 1) \]  

Table 2 Refractive Index values of cantilever ARROW waveguide

| SL No | Layers                        | RI     |
|-------|-------------------------------|--------|
| 1     | Silicon nitride core          | 2.00 + j0 |
| 2     | Silicon dioxide First cladding| 1.46 + j0 |
| 3     | Silicon Nitride Second cladding| 2.00 + j0 |
| 4     | Silicon substrate             | 3.85 + j0.019 |
| 5     | Superstrate                   | 1 + j0  |

Fig. 5 Directional view of microcantilever ARROW device

here, N, m are values 0,1,2 etc.,
transvers electric (TE) and transvers magnetic (TM) modes are present in the ARROW-B cantilever structures. The TE mode is used for the analysis purpose.

### 2.2.3 Optical Method

In optical method used for coupling of light from input waveguide to output waveguide in the ARROW-B cantilever. The light confinement inside the device is modelled by using optical modeling method. The center of the cantilever waveguide is designed using the below Eq. (7) [29].

\[
w(l) = w_0 \left[ \left( 1 + \frac{\lambda l}{\pi a_0^2} \right) \right]^{1/2}
\]  

(7)

Here, \( w_0 \) is the beam in the cantilever waveguide, wavelength is \( \lambda \) and \( l \) is the length of the waveguide. The light coupling efficiency is modeled by using Eq. (8) [29]

\[
\eta = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \psi_2(x, y, l) \psi_3(x, y + d) dx dy \cdot \int_{-\rho_c}^{\rho_c} \int_{-\rho_c}^{\rho_c} \psi_2(x, y, l) \psi_4(x, y + d) dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \psi_1^2(x, y) dx dy \cdot \int_{-\rho_c}^{\rho_c} \int_{-\rho_c}^{\rho_c} \psi_2^2(x, y) dx dy}
\]

(8)

The mode profile of the input ARROW waveguide region is \( \psi_1 \), the for and second cantilever region, third air gap region and output waveguide region are having the mode profiles \( \psi_2 \), \( \psi_3 \) and \( \psi_4 \) respectively. \( l \) is the length and cantilever deflection is \( d \), the half width of the output waveguide is \( \rho_{ct} \), \( \rho_{out} \) and \( \rho_{ct} \) is the half width of the cantilever. The detailed structure showing the entire ARROW waveguide is represented in Fig. 6.

### 3 Results

In this section we discuss about the electrical actuating of the cantilever waveguide and as well as the quality factor of the ARROW cantilever waveguide by varying the air gap distance in the structure.

![Regions of microcantilever ARROW waveguide](image-url)
3.1 Results of Electrostatically Actuated Microcantilever Beam

The result of the electrostatically actuated microcantilever beam is discussed as follows. The displacement, electric potentials and capacitance effects are the important parameters considered to analysis sensing ability of both cantilever beam and ARROW microcantilever waveguide respectively. The electrically applied voltage makes the deformation in the cantilever beam. The electrostatic field distribution is ensembles once the varying electric voltage applied at the cross-sectional point of two electrodes and thus exhibits a cantilever beam deformation which is estimated using Poisson theorem, as given in Eq. (9)

\[ \nabla \cdot (\varepsilon \nabla V) = 0 \]  

(9)

In the design of cantilever beam is required a proper modeling of mechanical and electrical interface. The coupled physics would be involved to extract the spatial coordinators after undergoes the interface derivatives. The electrical actuating of the microcantilever is achieved by the force applied in the positive feedback. As a result, the twists and bends of microcantilever beam are arrived once the distance gets prorogated with respect to voltage changes are achieved at the regular intervals. If the applied voltage reaches to particular value, then, the chance of beam collapses, which is referred as pull-in-voltage. At this particular time the system becomes unstable.

The system is covered with insulators on order to avoid the unnecessary losses. The boundary condition at the terminal is evaluated using the force density and is depicted in Eq. (10).

\[ F_{es} = -0.5(E.D)n + (n.E)D \]  

(10)

where, E is the electric field applied between two electrodes, D is displacement marked from outward vector of the boundary. Navier’s equation is used for estimating microcantilever beam coordinate system in the equilibrium state. Figure 7 shows the displacement of the cantilever beam along the z-axis. The electric potential across the microcantilever beam is indicated in Fig. 8.

The applied voltage on the silicon nitride microcantilever simulation leads the displacement in the cantilever along z direction is shown in Fig. 9. It is conveyed that the
increment of arc length with different electric voltages are directly affects the displacement. The shape of the cantilever beam for different applied voltage is shown in Fig. 9.

Figure 10 depicts the bending of the cantilever due to force acting on it. The displacement field orientation direction is in z-axis. When voltage of $V_0 = 1$ V is applied, the measured displacement is zero. From voltage values of 2–5 V the cantilever beam undergoes deformation. When the voltage is 6.0755 Volts i.e., when it reaches the pull-in voltage the cantilever based electrostatically actuated microcantilever collapses and becomes unstable.

The Fig. 11 depicts the microcantilever beam DC capacitance curve. The action is comparable to that of the parallel plate capacitance effect. Applied voltage makes the beam to soften. When softening occurs deformation continuous upon applying the voltage. Importance is to maintain the potential difference between the two electrodes in the microcantilever system modeled. As observed in the Fig. 11 capacitance values are from 36 to 62fF.
3.2 Quality Factor Calculation of Microcantilever ARROW Waveguide

Quality factor for the microcantilever ARROW B waveguide is analyzed. Quality factor or Q-factor is the ratio of resonant wavelength to full width half maximum (FWHM) and Q-factor is depicted in the Eq. (11). The electromagnetic (EM) wave is involved in the mathematical modelling of ARROW B cantilever waveguide. The 2.5D FDTD simulation is having the EM field in all region of operation. Since field is not decaying completely in the FDTD modeling the quality factor is calculated using slope of the decaying signal using the Eq. (12) shown.
In the above equations $\omega_r$ is the resonant frequency of the decaying signal. $m$ is the slope of the signal. The simulation is conducted by varying the gap distance between the output waveguide and cantilever i.e., air gap distance. The reported Q-factor also called as quality factor are comparable with the result obtained in article [3]. Q-factor obtained for the air gap distance of 2 µm is 15.10. The gap distance and its corresponding Q-factor and wavelength values are tabulated in the Table 3.

The graph of the Q-factor and wavelength for different values of the air gap distance is shown in Fig. 12.

### Table 3  Q-factor for cantilever ARROW-B

| Gap distance | Q-factor | Wavelength in nm |
|--------------|----------|------------------|
| 2            | 15.10    | 506.932          |
| 5            | 14.23    | 500.002          |
| 6            | 13.31    | 498.251          |
| 7            | 12.24    | 496.231          |

\[
Q = \frac{\omega_r}{FWHM} \tag{11}
\]

\[
Q = \frac{-\omega_r \ast \log_{10}e}{2m} \tag{12}
\]

In the above equations $\omega_r$ is the resonant frequency of the decaying signal. $m$ is the slope of the signal. The simulation is conducted by varying the gap distance between the output waveguide and cantilever i.e., air gap distance. The reported Q-factor also called as quality factor are comparable with the result obtained in article [3]. Q-factor obtained for the air gap distance of 2 µm is 15.10. The gap distance and its corresponding Q-factor and wavelength values are tabulated in the Table 3.

The graph of the Q-factor and wavelength for different values of the air gap distance is shown in Fig. 12.

### 4 Discussion

In this section we discuss the light intensity analysis of the ARROW-B microcantilever waveguide with respect to its x-axis and also sensitivity analysis of the device modeled.
4.1 Intensity Analysis

Electric field intensity for the cantilever beam in the ARROW waveguide is modeled and analyzed. Power and field monitors are used to find the E-field intensity. The light source used in the simulation process is in the spectral range from 400 to 700 nm. The spectrum of the light source used is shown in the Fig. 13. Modal analysis of the ARROW microcantilever waveguide is carried at wavelength 632.8 nm in the visible spectrum.

The Fig. 14 shows the electric field intensity curve of the cantilever waveguide region. The measured intensity is at the input cantilever waveguide region and at the output.
waveguide. The power monitors are used to obtain the intensity spectrum. The 2.5D or variational FDTD is the method used for modeling the ARROW B cantilever waveguide. The power monitor gives the electric field, magnetic field and pointing vector details. The perfectly matched layer boundary conditions are used to minimize the light absorbance from the device.

The intensity of the light decreases when it is propagating along the cantilever structure and mathematically is represented by the Eq. (13)

\[ P(x) = P_0 \exp(-\alpha x) \]  

(13)

In Eq. (13) the \(\alpha\) absorption parameter, \(P_0\) is the power given to the cantilever \((x = 0)\). The output power analysis of the presented work satisfies the above power analysis equation.

4.2 Sensitivity

The designed model is simulated by considering the surrounding material as air and also as liquid. When fluid is used for simulation such as blood sample with refractive index 1.33 and hemoglobin refractive index is 1.3854 [31]. The behavior of the system is discussed in this section along with sensitivity. Flow of fluid in the waveguide is laminar and Newtonian and it satisfies the Navier stokes Eq. (14) as shown depicted below [3].

\[
\rho \frac{dv}{dt} + \rho (v \cdot \nabla) v = -\nabla p + \mu \nabla^2 v
\]

(14)

Here, the density is \(\rho\) and velocity is \(v\) and pressure is represented as \(p\). Viscosity of the fluid is \(\mu\).

The Reynolds number of the device is given by Eq. (15).

\[
Re = \frac{\rho \nu}{\mu} = \frac{\rho \nu b^2}{4 \mu}
\]

(15)

The simulation is carried out for both air and blood as surrounding material. The fluid flow modeling is simulated with the design is Newtonians and Eq. (14) and (15) are used in the simulation of the fluid interaction. The sensitivity of the sensor is the ratio of change in the wavelength with respect change in the refractive index of the analyte used. The sensitivity is given by Eq. (16). The reported sensitivity for different analyte refractive index is given in Table 4. The average sensitivity with our work is 73.78 nm/RIU. The obtained sensitivity is comparable with the sensitivity values obtained in article [6]. The variation in the refractive index of the material is denoted as refractive index unit (RIU). The Fig. 15 shows wavelength versus refractive index plot for the different analyte concentration.

| Sl no | RI     | Q-factor | Wavelength in nm | Sensitivity (nm/RIU) |
|-------|--------|----------|------------------|----------------------|
| 1     | 1      | 25.183   | 766              | 75.75                |
| 2     | 1.33   | 24.257   | 791              | 71.81                |
| 3     | 1.3857 | 24.048   | 795              | –                    |
Sensitivity is the main design parameter while designing sensor. The designed and simulated ARROW microcantilever waveguide can be used as refractive index-based sensor in medical application. The air gap distance of one micron is considered while designing the sensitivity analysis. The variation of the sensitivity upon changing the refractive index of the surrounding fluid are listed in Table 4. The change in RI versus sensitivity plot is depicted in Fig. 16.

\[ S = \frac{\Delta \lambda}{\Delta n} \]  

(16)
5 Conclusions

The simulation and modeling of the microcantilever beam and microcantilever ARROW waveguide has been presented. The designed ARROW microcantilever waveguide is a refractive index-based sensor has application in biomedical field. The changes in the refractive index results in change of the wavelength of the device. The length, width and thickness of silicon nitride microcantilever is $300 \times 40 \times 20 \, \mu m$ simulated using finite element method. The electrostatic voltage is applied to the cantilever using the electrodes present in the insulated chamber. The designed system acts like a parallel plate capacitor. The changes in the displacement for applied voltage and capacitance are measured. The ARROW microcantilever waveguide is the second structure designed and simulated using visible light. The waveguide has $400 \times 10 \times 10 \, \mu m$ length, thickness and width in dimension. The ARROW microcantilever is simulated and analyzed for different refractive indices values. The sensitivity of the sensor has good response and reproducible analytic sample in lab-on-a-chip application.

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Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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