Modeling of SPR ARROW Structures for Lab-On-a-Chip Application

Suryanarayana N K
Dept. of ECE
Sai Vidya Institute of Technology, Affiliated to VTU, Belagavi
Bengaluru, India
suryanarayana.nk@saividya.ac.in

Asha K
Dept. of ECE
BMS Institute of Technology, Affiliated to VTU, Belagavi
Bengaluru, India
ashak@bmsit.in

Venkatesha M
Dept. of ECE
Sai Vidya Institute of Technology, Affiliated to VTU, Belagavi
Bengaluru, India
Venkatesha.m@saividya.ac.in

Narayan K
Department of Artificial Intelligence &Machine Learning
Nitte Meenakshi Institute of Technology, Affiliated to VTU, Belagavi
Bengaluru, India
narayank101@gmail.com

ABSTRACT

ARROW waveguides are the micro electro opto mechanical devices used in the bio medical application. Surface plasmon resonance ARROW waveguide is modelled and analyzed. These Photonic devices are based on light interaction on the waveguides. Visible wavelength is used for the modelling. These are integrated optical structure used to enhance the technology in the Lab-On-a-Chip market. The main parameter measuring with this device is Quality factor of the structure and transmission spectrum analysis.

Keywords—ARROW waveguide; SPR Bio sensor; Quality factor ; Transmission; Biosensor;

I. INTRODUCTION

Planar slab waveguides are the structures used in photonics sensing and biomedical applications. Silicon dioxide-based grating structures [1], slab dielectric waveguides [2-4], anti-resonant reflecting waveguide structures are used. These devices are also having application as modulator, optical switches, filter circuits, switched directional couplers, in communication system [2]. For modeling and analysis of these structure Eigne value theorem [5] and finite element method and Finite difference time domain methods are involved. These devices are the part of the integrated optics. Modelling of blood flow pulse rate is with the help of Non-invasive method. The different health issues such as internal bleeding hypovolemia may be detected using static magnetic field approach [6].

The ARROW waveguide are low loss devices formed on Glass or Silicon substrate. These devices can be integrated with optical and electrical components, and they are the micro opto electronic circuits [7]. Multilayer ARROW structures are also part of the electronics circuits. These devices use the high index substrate material and are suitable as a polarizer device [8], and as Photodetectors [9]. The large light confinement of light is possible with ARROW waveguide devices. Single mode propagation of light is possible effectively with ARROW structure [10]. Spectral characteristics of liquid core ARROW waveguides are analyzed and fabricating using the chemical vapor deposition method [13]. Analyzing leaky modes of these waveguides are part of the design and implementation. Photonic crystal fiber (PCF) based structures are implemented for sensing using magnetic fields [14].

Optofluidic chip are the sensing platform in the bio-medical application. The coupling of light is increased from 82% to 95% wit this article. The detection of fluorescent particle is carried out [15]. Efficient way of detection of colour change is possible with small nano or Pico liter capacity of liquid core waveguide (LCW). These structures are the hallow core ARROW devices. These are fabricated using multilayers of SiN/SiO_2 materials and these are part of the Lab-On-a-Chip sensor devices [16-19].

Micro opto electro mechanical devices are and its applications in application and classification is shown in figure 1. We can design sensor using passive components or as active components. Actuators, cantilever waveguides, resistive sensors, photo diodes, detector etc., The different examples are shown in figure below.

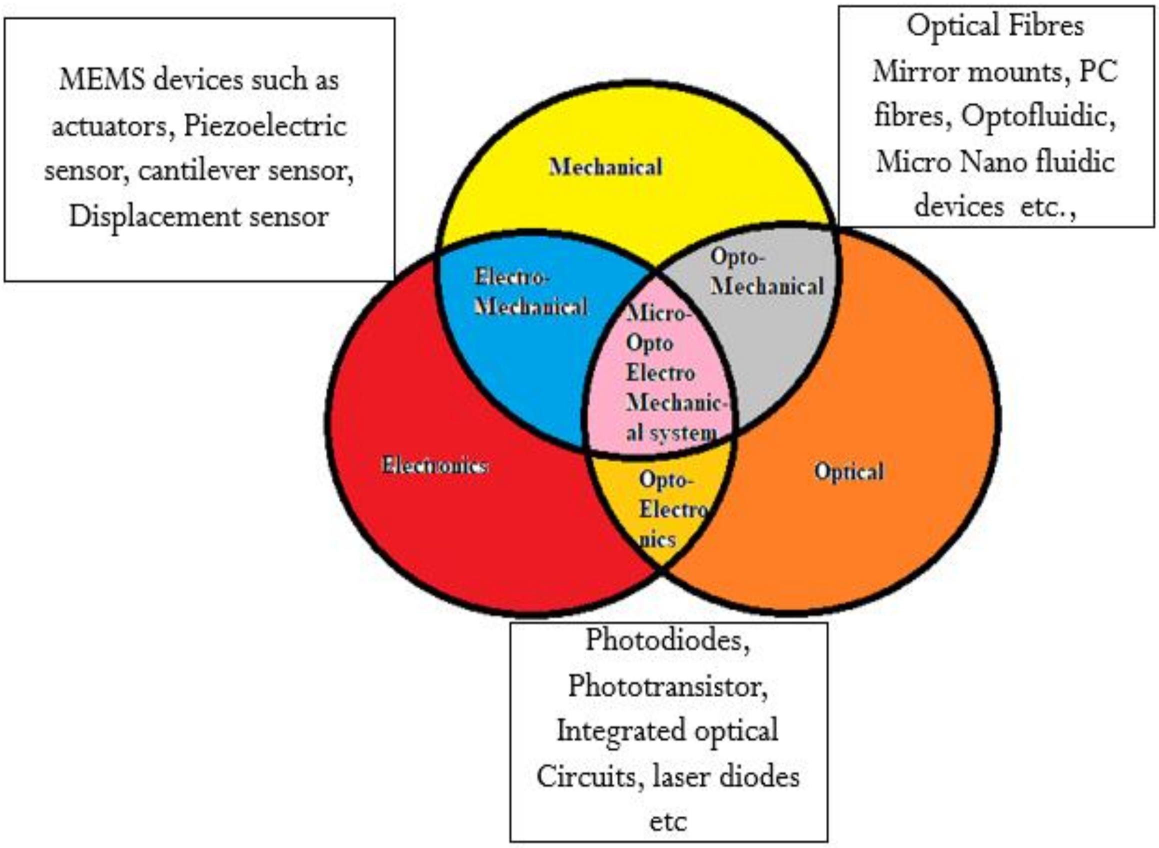

Figure 1: Micro Opto Electro Mechanical System based devices classification

Variational FDTD uses time domain Maxwell's equations to solve various optical modal parameters of waveguide structures. The times varying Maxwell's equations are discussed. The equation (1) is called as Gauss law intended for electric fields. Magnetic field in the electromagnetics is given by Gauss law for magnetic fields as shown in equation (2). Faradays law is shown in equation (3) and equation (4) shows the Ampere Maxwells law.

$$\nabla . E = \frac{\rho}{\varepsilon_0} \tag{1}$$

$$\nabla . B = 0 \tag{2}$$

$$\nabla \times E = \frac{\partial B}{\partial t} \tag{3}$$

$$\nabla \times B = \mu_0 j + \frac{1}{C^2}\frac{\partial E}{\partial t} \tag{4}$$

II. SPR ARROW WAVEGUIDE STRUCTURE

The ARROW waveguide devices contain high index core and first cladding and low index second cladding and a Silicon semiconductor substrate [9]. The first cladding thickness for ARROW SPR waveguide is calculated using below equation (5) [9-12].

$$d_1=\frac{\lambda}{4n_1}[1-(\frac{n_c}{n_1})^2+(\frac{\lambda}{2n_cd_c})^2]^{-0.5}(2N+1) \tag{5}$$

Where $\boldsymbol{d_1}$ is thickness of first cladding layer, $\boldsymbol{\lambda}$ is the wavelength, core thickness is $\boldsymbol{d_c}$, core refractive index (RI) is $\boldsymbol{n_c}$, $\boldsymbol{n_1}$ is RI of first cladding and $\boldsymbol{n_2}$ is RI of second cladding. The second cladding thickness is calculated using the below equation (6)

$$d_2=\frac{d_c}{2}(2M+1) \quad \text{N, M= 0, 1, 2, …} \tag{6}$$

Solid core ARROW waveguides dependents on the x and y polarization. It is used to calculate the loss in the device [18]. The intensity of device is given by the equation (7) below.

$$I_0=I_ie^{-\alpha_xL}cos^2(\theta)+I_ie^{-\alpha_yL}sin^2(\theta) \tag{7}$$

Along with intensity the other parameters measured are transmission, FWHM and lateral displacements in radians [21]. The different structures are couplers, MZI based ARROW devices [22], vertical cavity ARROW devise [23], and multi-mode interference ARROW device [24-25].

These SPR ARROW bio sensor are the devices used as a Lab-on-a-chip application. These are applicable in the optofluidic microsensors. The transfer electric and magnetic field is analyzed in this design. The fabrication methods are PECVD, atomic layer deposition (ALD) [28-31]. Plasmonic structures are used as the refractive index sensor [26-27]. Surface Plasmon Resonance (SPR) ARROW waveguide is shown in figure 2. The Design parameters and its materials are listed in table 1.

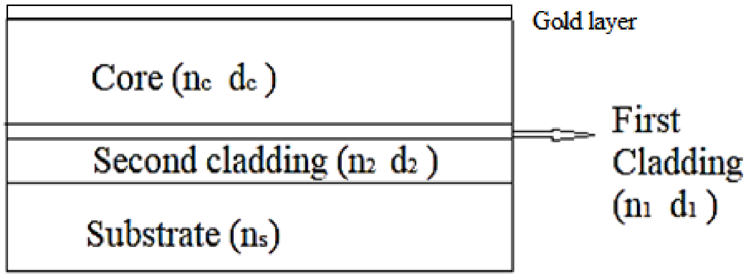

Figure 2: SPR ARROW Waveguide structure

Table 1: Design parameters of SPR ARROW-B waveguide [7]

Layer	RI	Material Used	RI Value
Core and Second cladding	$n_c=n_2$ greater than n_1	As_2S_3	1.87
		NA45 glass	1.54
		C7059	1.54
		TiO_2	2.3
		Si_3N_4	2.0
		ZnO	1.98
		Al_2O_3	1.65
		ZrO_2	1.92
First Cladding	$n_1 << n_c$	SiO_2	1.46
		CaF_2	1.43
Substrate	$n_s >> (n_1, n_c, n_2)$	Si, Ge, GaAs, InP other semiconductors	--

The propagation constant of the SPW at the metal dielectric layer is given by below equation (8) [32]

$$k_{SPW} = k_0 \sqrt{\frac{\varepsilon_m X\, \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \tag{8}$$

Where $k_0$is the optical wave free space wave number. $\varepsilon_m$is metal permittivity and $\varepsilon_d$is the dielectric permittivity. The result and discussion are elaborated in below section.

III. RESULTS AND DISCUSSION

SPR ARROW waveguide transmission spectrum is shown in figure 3. The different materials are used for the simulation are listed in table 1 with corresponding Refractive Index. For Aluminum dioxide the transmission percentage is more compared to all other materials.

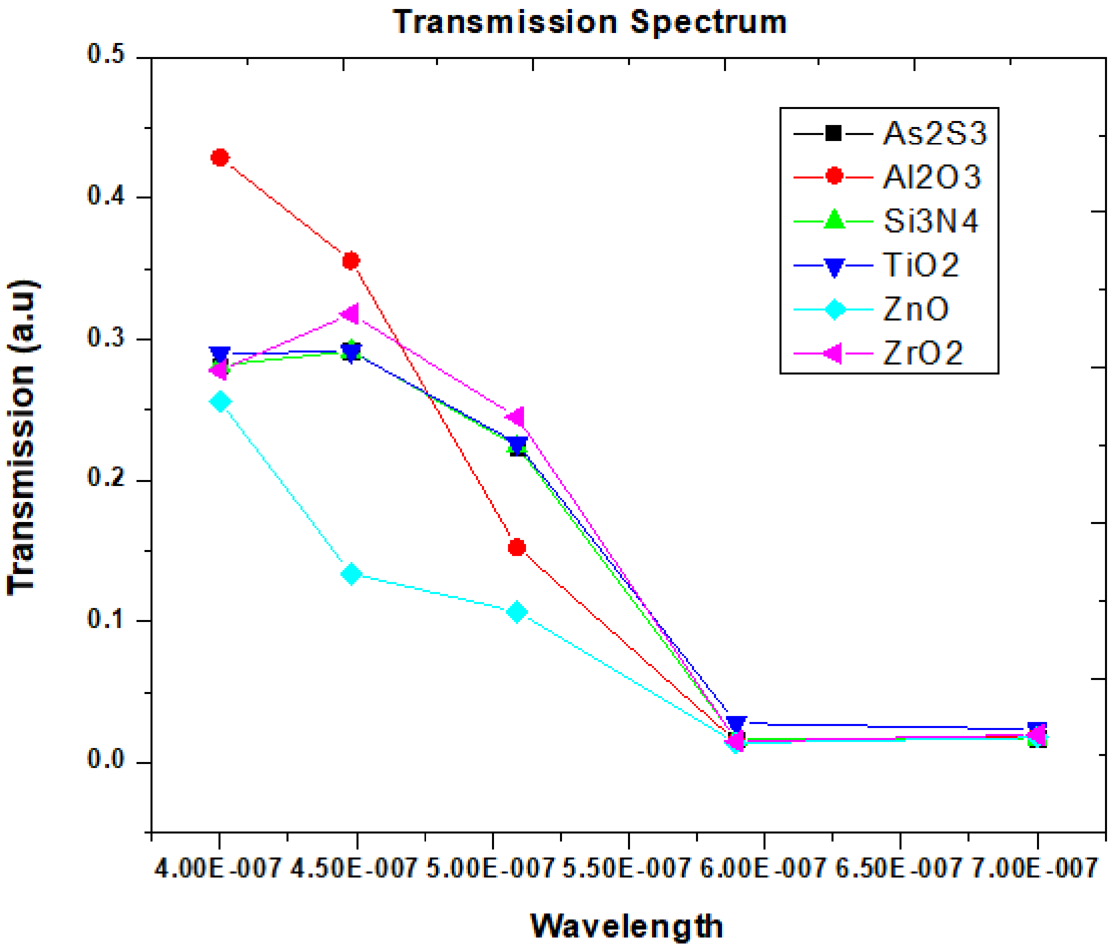

Figure 3: Transmission Spectrum of ARROW-B Waveguide

Quality factor for ARROW-B waveguide is defined by the formula which is shown in equation (9) [33]

$$Q = \frac{-2\pi f_r * \log_{10} e}{2n} \tag{9}$$

$f_r$is the decaying signal resonant frequency, and n is the signal slope. Alteranate equation used to find the Q-factor is given in equation (10). Table 3 list the wavelength and cossesponding quality factor for two different resonance 1 and resonance 2.

$$Q = \frac{2\pi f_r}{FWHM} \tag{10}$$

Where, FWHM is the full width half maximum of the resonant spectrum. The values of quality factors for different core material of the ARROW materials are listed below.

Table 3: Quality factor values

Material	Resonance 1		Resonance 2	
	Wavelength (nm)	**Q**	**Wavelength (nm)**	**Q**
As_2S_3	594.02	66.13	464.14	66.51
Al_2O_3	464.82	79.74	480.31	94.66
Si_3N_4	465.38	73.19	481.75	64.71
ZnO	462.03	58.96	477.70	61.72
ZrO_2	470.14	110.32	477.58	108.52
TiO_2	545.85	97.50	486.23	285.24

IV. CONCLUSION

SPR ARROW structure are promising structure used as a refractive index-based sensor. The variation of the ARROW waveguide is SPR ARROW waveguide for bio sensing application. In this work variation in RI results in the changes in resonant wavelength. The sensitivity is the ratio of the changes in the peak wavelength to the RI variation. The modeled SPR ARROW waveguide has effective index of $1.9+2.4*10^{-6}$ and minimal loss reported is 0.00034 dB/cm. The quality factor is measured for various core materials.

REFERENCES

[1] Jozef, Chovan, Uherek František, Kuzma Anton, Eduard Koza, and Patassy Gabor. "Design and investigation of SiO2 slab waveguide grating for photonics sensing application." In *2014 24th International Conference Radioelektronika*, pp. 1-4. IEEE, 2014.

[2] Kogelnik, H. "Review of integrated optics." *Fiber & Integrated Optics* 1, no. 3 (1978): 227-241.

[3] Helmers, H&on, P. Bettech, and R. Rimet. "Integrated optical components employing slab waveguides for sensor applications." *IEEE Photonics Technology Letters* 8, no. 1 (1996): 81-83.

[4] Asha, K., N. K. Suryanarayana, K. Narayan, and P. K. Pattnaik. "Design and Modeling of Microfluidic Channel in a Dielectric Planar Waveguide Using Cosmol Multiphysics." In *Emerging Research in Computing, Information, Communication and Applications*, pp. 79-87. Springer, New Delhi, 2016.

[5] Raghuwanshi, S. K., and Santosh Kumar. "Derivation of dispersion equation by using the equivalent transmission line method for the case of planar slab optical waveguide structure." In *2012 International Conference on Optical Engineering (ICOE)*, pp. 1-4. IEEE, 2012.

[6] Atalla, Ashraf, Kaustubh Nagarkar, and Jeff Ashe. "Modeling the magnetic disturbance of pulsatile blood flow in a static magnetic field." In *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 1406-1409. IEEE, 2014.

[7] Y., T. Baba, T. Sakaki, and K. Iga. "Low-loss antiresonant reflecting optical waveguide on Si substrate in visible-wavelength region." *Electronics Letters* 22, no. 17 (1986): 892-893. https://doi.org/10.1049/el:19860608.

[8] Duguay, M. A., Y. Kokubun, Thomas L. Koch, and Loren Pfeiffer. "Antiresonant reflecting optical waveguides in SiO2-Si multilayer structures." *Applied Physics Letters* 49, no. 1 (1986): 13-15. https://doi.org/10.1063/1.97085. [uma] [JARDCS-9]

[9] Baba, Toshihiko, and Yasuo Kokubun. "High efficiency light coupling from antiresonant reflecting optical waveguide to integrated photodetector using an antireflecting layer." *Applied optics* 29, no. 18 (1990): 2781-2792. https://doi.org/10.1364/AO.29.002781.

[10] Baba, Toshihiko, and Yasuo Kokubun. "Dispersion and radiation loss characteristics of antiresonant reflecting optical waveguides-numerical results and analytical expressions." IEEE Journal of Quantum electronics 28, no. 7 (1992): 1689-1700. https://doi.org/10.1109/3.142556.

[11] K. Asha, M. Uma, M. Neveditha, G. S. Srinivas, R. Shashank and K. Narayan, "Modeling and Analysis of ARROW Waveguide for Point of Care Diagnostic Application," 2018 2nd International Conference on Trends in Electronics and Informatics (ICOEI), Tirunelveli, India, 2018, pp. 951-954, doi: 10.1109/ICOEI.2018.8553860.

[12] K. Asha, M. Poojashree, D. J. Manaswitha, K. Rajani, G. S. Harshitha and K. Narayan, "A Review On Liquid Core Waveguide based MOEMS Structures," *2019 3rd International Conference on Trends in Electronics and Informatics (ICOEI)*, Tirunelveli, India, 2019, pp. 609-612, doi: 10.1109/ICOEI.2019.8862510.

[13] Bernini, Romeo, Elbano De Nuccio, Aldo Minardo, Luigi Zeni, and Pasqualina M. Sarro. "2-D MMI devices based on integrated hollow ARROW waveguides." *IEEE Journal of Selected Topics in Quantum Electronics* 13, no. 2 (2007): 194-201. https://doi.org/10.1109/JSTQE.2007.894054.

[14] Gao, Ran, Dan-Feng Lu, Jin Cheng, Yi Jiang, Lan Jiang, Jan Sen Ye, and Zhi-Mei Qi. "Magnetic fluid-infiltrated anti-resonant reflecting optical waveguide for magnetic field sensing based on leaky modes." *Journal of Lightwave Technology* 34, no. 15 (2016): 3490-3495.

[15] Measor, Philip, Sergei Kühn, Evan J. Lunt, Brian S. Phillips, Aaron R. Hawkins, and Holger Schmidt. "Hollow-core waveguide characterization by optically induced particle transport." *Optics letters* 33, no. 7 (2008): 672-674.

[16] Yin, Dongliang, John P. Barber, Aaron R. Hawkins, and Holger Schmidt. "Highly efficient fluorescence detection in picoliter volume liquid-core waveguides." *Applied Physics Letters* 87, no. 21 (2005): 211111

[17] Archambault, J.L., Black, R.J., Lacroix, S. and Bures, J. Loss calculations for antiresonant waveguides. *Journal of Lightwave Technology* **11** (3) (1993) 416-423.

[18] Krishnaswamy, Narayan, Talabattula Srinivas, Gowravaram Mohan Rao, and Mukundan Manoj Varma. "Analysis of integrated optofluidic lab-on-a-chip sensor based on refractive index and absorbance sensing." *IEEE Sensors Journal* 13, no. 5 (2013): 1730-1741.

[19] Vandewiele, Stijn, Toon Brans, Liesbet Van Landschoot, Katarzyna Komorowska, Steven Verstuyft, Ananth Subramanian, Chen Hu, Filip Beunis, and Roel Baets. "Single-mode air-clad liquid-core waveguides on a surface energy patterned substrate." *Optics letters* 39, no. 16 (2014): 4942-4945.

[20] Yin, Dongliang, John P. Barber, Aaron R. Hawkins, and Holger Schmidt. "Waveguide loss optimization in hollow-core ARROW waveguides." *Optics Express* 13, no. 23 (2005): 9331-9336.

[21] Laine, J-P., B. E. Little, D. R. Lim, H. C. Tapalian, L. C. Kimerling, and H. A. Haus. "Microsphere resonator mode characterization by pedestal anti-resonant reflecting waveguide coupler." *IEEE Photonics Technology Letters* 12, no. 8 (2000): 1004-1006.

[22] Hsu, Shih-Hsin, and Yang-Tung Huang. "Design and analysis of Mach–Zehnder interferometer sensors based on dual strip antiresonant reflecting optical waveguide structures." *Optics letters* 30, no. 21 (2005): 2897-2899.

[23] Chen, N. S., and S. F. Yu. "Design and analysis of large-area vertical-cavity semiconductor optical amplifiers with anti-resonant reflecting optical waveguide." *Journal of lightwave technology* 24, no. 1 (2006): 526.

[24] Stott, Matthew A., Vahid Ganjalizadeh, Maclain H. Olsen, Marcos Orfila, Johnny McMurray, Holger Schmidt, and Aaron R. Hawkins. "Optimized ARROW-based MMI waveguides for high fidelity excitation patterns for optofluidic multiplexing." *IEEE journal of quantum electronics* 54, no. 3 (2018): 1-7.

[25] Stott, Matthew A., Vahid Ganjalizadeh, Gopikrishnan Meena, Johnny McMurray, Maclain Olsen, Marcos Orfila, Holger Schmidt, and Aaron R. Hawkins. "Buried Rib SiO 2 Multimode Interference Waveguides for Optofluidic Multiplexing." *IEEE Photonics Technology Letters* 30, no. 16 (2018): 1487-1490.

[26] Sinha, R. K., and R. Bhattacharyya. "Analysis and design of hybrid ARROW-B plasmonic waveguides." *JOSA A* 30, no. 8 (2013): 1502-1507.

[27] Romeo Bernini, Stefania Campopiano, Luigi Zeni, Pasqualina M. Sarro, "ARROW optical waveguides based sensors*," R. Bernini et al./Sensors and Actuators B 100 (2004) 143–146*

[28] Testa, Genni, Gianluca Persichetti, and Romeo Bernini. "Liquid core ARROW waveguides: a promising photonic structure for integrated optofluidic microsensors." *Micromachines* 7, no. 3 (2016): 47.

[29] Huang, Chi-Chieh, Hsin-Feng Hsu, Sz-Hau Chen, Kun-Yu Tsai, Yang-Tung Huang, Chih-Sheng Lin, and Shih-Hsin Hsu. "Real-time detection of α-thrombin binding to single-strand DNA aptamers by a highly sensitive Si-based waveguide SPR biosensor." In *Third Asia Pacific Optical Sensors Conference*, vol. 8351, pp. 601-605. SPIE, 2012.

[30] Huang, Yang-Tung, Wei-Zung Chang, Shih-Hsin Hsu, Chun-Ho Chen, and Jou-Chien Chen. "Antiresonant reflecting optical waveguide surface plasmon resonance sensors." In *Device and Process Technologies for MEMS and Microelectronics II*, vol. 4592, pp. 299-306. SPIE, 2001.

[31] Hsu, Hsin-Feng, Zheng-Wen Lin, Yang-Tung Huang, and Chiun-Jye Yuan. "Real-time detection of protein kinase a activity by a Si-based ARROW-B SPR biosensor." In *2013 Conference on Lasers and Electro-Optics Pacific Rim (CLEOPR)*, pp. 1-2. IEEE, 2013.

[32] Hsu, Hsin-Feng, Yen-Ting Lin, Yang-Tung Huang, Ming-Feng Lu, and Chyong-Hua Chen. "In Situ Regeneration of Si-based ARROW-B Surface Plasmon Resonance Biosensors." *Journal of medical and biological engineering* 35 (2015): 305-314.

[33] Asha, K., Krishnaswamy, N. & Suryanarayana, N.K. Analysis of ARROW Waveguide Based Microcantilever for Sensing Application. *Wireless Pers Commun* **126**, 3435–3453 (2022). https://doi.org/10.1007/s11277-022-09872-y