PARALLEL PLATE STRUCTURES FOR OPTICAL MODULATION AND CASIMIR FORCE MEASUREMENT

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Abstract
Integrated optical switches using mechano-optical sensing are gaining more attention in many fields due to their fast switching speed, large bandwidth and compact devices. In this paper, a micromachined electrostatically actuated metal plate to sense the evanescent field above the waveguide is presented. The feasibility of MEMS based light weight mechanical plates to achieve fast switching is evaluated. With decreasing distance between the suspended plate and the substrate it gets more difficult to control the gap due to forces resulting from parasitic charging and the Casimir effect. Measurement of the Casimir force between parallel plates at sub-micron distance is also cumbersome. A methodology to measure the Casimir force between parallel plates is presented here. The prime objective of this research is to come up with an ultra fast optical switch using parallel plates and also to measure the Casimir force between them.

Keywords*: *Parallel plates, evanescent field sensing, electrostatic actuation, casimir force

I- Introduction

Parallel plate structures have many applications in power sensors, electro-mechanical tuning, and electrical and optical switches. With the help of micromachining techniques, it is possible to fabricate parallel plates with an extremely small gap between them. The research presented in this paper focuses on using a micromachined suspended plate structure in an optical switch with fast switching speed [1]. A conventional optical switch involves electro-optic coupling between optical waveguides which has limited use and applications. In the early 90's, studies have shown that a movable mechanical plate can introduce loss into the optical path by sensing the evanescent field surrounding the waveguide [2]. Fast switching can be achieved by using electrostatic actuation [3], [4]. As the distance for such devices should be in the sub-micron range, it gets difficult to control the parallelism and stiction caused by the forces due to parasitic charging and the Casimir effect. Therefore, an investigation to measure the Casimir force in a parallel plate configuration is carried out.

The Casimir force as predicted by Hendrik Casimir over 50 years ago influences both the macro and nano world. It is well defined as an attractive force occurring due to vacuum fluctuations between conductive parallel plates [5]. For many years, little research was performed concerning the Casimir force. In the late 90's, experimental physicist started realizing that the Casimir force affects the working of micro and nano level devices. It plays a major role in causing instability of the devices formed of parallel plates and is considered to be one of the major causes for stiction and gumming up of micro and nano devices [6], [7]. Many have succeeded in measuring the Casimir force with geometries involving a sphere and a plate, but very few have attempted this with parallel plates [8]. The first attempt with a parallel plate geometry dates back to Sparnay's experiment with two metallic mirrors in parallel [9]. With the advancements in instrumentation and MEMS technologies, it is becoming feasible to measure this force between parallel plates with better precision.

The basic Casimir force formula is valid only under ideal conditions and consequently there have been many correction factors involved such as finite conductivity and roughness of metal plates [10]. Experimental study including the correction factors was possible only with sphere-plate geometry due to its agreeable precision. Another important correction factor involved is due to temperature effects, as the original calculation was made at zero temperature, but the actual experiments are generally performed at room temperature [11].

II- Optical Modulation

Evanescent Field Sensing

When light is impinged at the core cladding interface of optical fibres and waveguides, a part of the optical power always penetrates into the lower refractive index medium. This field is called the evanescent field, which decreases exponentially with the distance from the boundary of core. Optical modulation by sensing this field is achieved by moving a plate above the waveguide as shown in figure 1. In this figure, the separation between the suspended plate and the waveguide is varied by the displacement caused by electrostatic actuation of the top plate. Due to the electrostatic force acting on it, it is pulled down, causing the plate to move into the evanescent field surrounding the waveguide. A metallic plate with complex refractive index is most suitable to be used as the suspended plate, since it introduces absorptive loss into the optical waveguide, thus performing an ON/OFF switching mechanism.

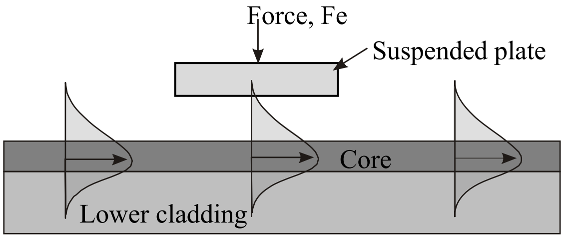


Fig.1: Schematic drawing of a suspended plate in the evanescent field above a waveguide

A simulation study to analyze the separation between the suspended metal plate and waveguide was carried out using the FieldDesigner tool [12]. It clearly shows that the loss due to the metal layer decreases with increasing gap distance. It is also observed that air medium between the suspended metal plate and optical waveguide facilitates the effective sensing of the evanescent field. The loss of optical power into the substrate, which normally has higher refractive index than the waveguide material, is also studied and the results are shown in figure 2. A Triplex waveguide was chosen for the simulation study as it has low optical attenuation and low polarization effects compared to other optical waveguides [13].

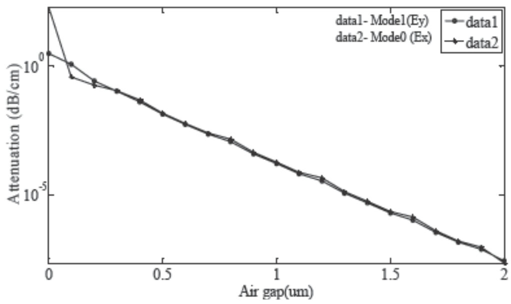
Electrostatic Actuation

The response of electrostatic actuation between parallel plates in general is nonlinear and causes pull-in effect. This unstable pull-in effect is used in this study to enhance the switching mechanism. The focus of this research being the fast switching mechanism using mechano-optical sensing, an analytical approach to show the possibility of achieving 1 µs as switching time is accomplished. The analysis started with the fundamental dynamic equation of motion of a suspended plate:

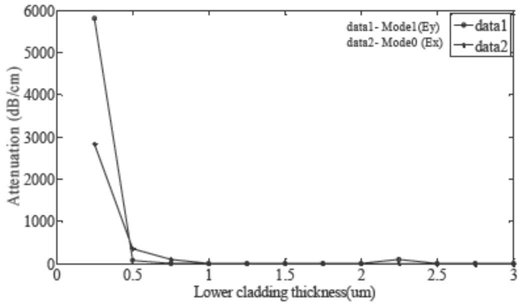
$$m\frac{d^2x}{dt^2} = -K(x - x_0) - D\frac{dx}{dt} + F_{el}$$

With m the mass of the plate, K the spring constant of the suspension and D the damping constant.
For a parallel plate configuration with plate separation x and area A, the electrostatic force F_{el} as a function of voltage V is given by:

$$F_{el} = \frac{\varepsilon_0 A V^2}{x^2}$$



(a)



(b)

Fig. 2: Loss due to the suspended metal plate as a function of the separation distance (a) and substrate loss as a function of the lower cladding thickness (b) calculated using the FieldDesigner tool.

Figure 3 shows the switching time estimation using Matlab/Simulink with realistic values for the mass and spring constant. A short, 65 V pulse is used to get the plate moving. The voltage is reduced to a few volts just before the plate's collapse, which is sufficient to keep the movable plate pulled-in. It is evident from the analysis that a light weight movable plate can introduce ON/OFF switching of optical signal in just 1 µs.

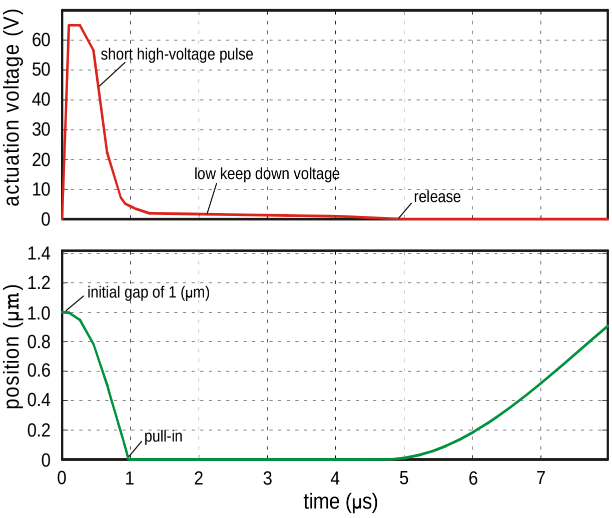


Fig. 3: Switching time estimation using Matlab/ Simulink

Fabrication Methodology

The suspended metal plate is designed to be fabricated with a combination of bulk and surface micromachining techniques at the wafer level. Various types of spring designs are implemented to optimize the design for short and fast movement of suspended plate. As the electrostatic actuation will be applied between the substrate and an Au layer on top of the moveable structure, a highly conductive substrate is used. The suspended plate consists of low-stress silicon-rich silicon nitride (SiRN) and is strengthened by silicon nitride ridges underneath the plate. These ridges are made by refilling etched trenches with SiRN. Polysilicon is used as sacrificial material since it can be etched with high selectivity and it is also compatible with high temperature processing. Figure 4 shows an illustration of the fabrication process. Figure 5 shows a photograph of a moving plate structure just before the final sacrificial layer etching step. XeF_2 etching will be used to release the structures, which has nearly infinite selectivity to silicon over materials including photoresist, silicon dioxide, silicon nitride and aluminum.

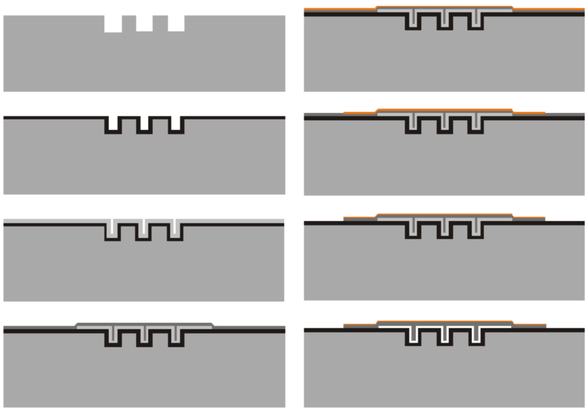


Fig.4: Fabrication process flow for suspended plate for optical switching – a) Etching trenches in Si wafer, b) Wet oxidation of Si for 1 µm, c) LPCVD of Poly-Si as sacrificial layer, d) Patterning Polysilicon & LPCVD of Silicon nitride (SiN)(refilling of trenches), e) Sputtering of gold, f) Patterning of gold, g) Etching of SiN, h) Release of structures.

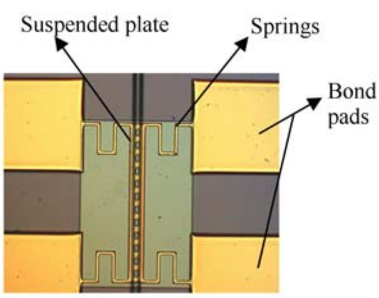


Fig.5: Photograph of fabricated test structure just before etching the sacrificial polysilicon layer.

III- Casimir Force Measurement

Casimir Force Theory

The Casimir force is quantitatively defined as:

$$Fc = \frac{\pi^2 \hbar c}{240 d^4} A$$

Where Planck's reduced constant, $\hbar$, and the velocity of light, c, are the only fundamental constants independent of electronic charge. The surface area of plate, A, and the distance between the parallel plates, d, are the only variable parameters in the equation. The dimensions of the plate A should be much larger than the separation distance d.

Measurement Set up

The proposed measurement set up in this research consists of a parallel plate configuration in which one plate is suspended by springs. The other plate is actuated at a small, fixed amplitude in order to modulate the Casimir force. Figure 6 shows the calculated Casimir force and the resulting deflection amplitude of the suspended plate using surface areas of 1mm^2. The separation distance is varied from 50 nm to 1 µm. The deflection will be measured using a laser vibrometer, giving a lower limit to the measurable displacements in the order of picometers.

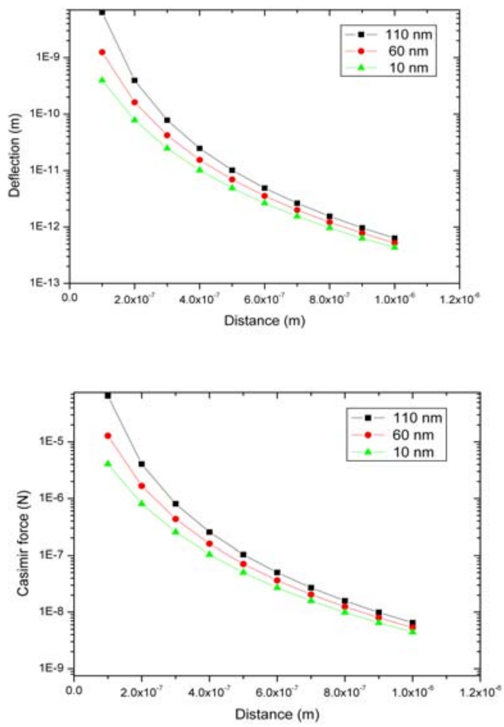


Fig.6: Deflection of the movable plate and the corresponding Casimir force as a function of varying gap distance between the plates.

Fabrication of smooth surfaced plates with springs attached to the plates is also devised. It is more important that the surface roughness should be as low as possible, so that it facilitates the measurement to the lowest possible separation of 50 nm. Anisotropic wet chemical etching of <111> oriented wafers have shown to yield smooth surfaced parallel beams and membranes [14]. This is being used in our fabrication process to get a smooth surfaced plate. Figure 7 show the top and cross sectional views of test structures. Fabrication of these test structures for the examination of surface roughness and the validation of parallel plates with spring structures has recently started.

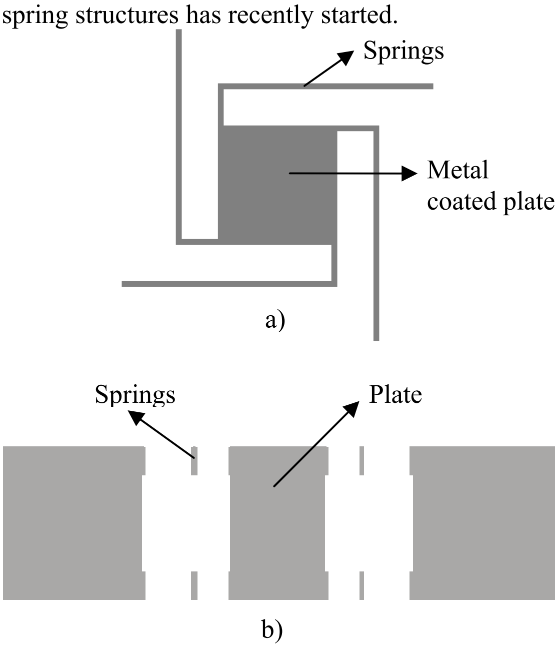


Fig.7: a) Top view of proposed parallel plate structures, b) Cross sectional view

IV- Conclusion

This paper presents an overview of application of parallel plate structures for optical modulation and to measure the Casimir force between them. This approach of optical modulation is compelling because of its light weight design and fast mechano-optical switching. We aim to come up with an ultra fast optical switch using evanescent field sensing that can be readily used in optical multiplexers and de-multiplexers. To enhance the functioning of micro and nano structures involving parallel plate geometry, it is essential to understand the underlying physical force as discussed here. Therefore, we are also aiming to measure this Casimir force between parallel plate geometry with better precision.

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