Characterization and Passivation Effects of an Optical Accelerometer Based on Antiresonant Waveguides

A. Llobera, J. A. Plaza, I. Salinas, J. Berganzo, J. García, J. Esteve, and C. Domínguez

***Abstract*—An optical accelerometer based on antiresonant reflecting optical waveguides is presented. The design consists on a quad beam structure where two waveguides are placed on the frame of the accelerometer, while a third is placed over the proof mass. When an acceleration is applied, a misalignment between the three waveguides is immediate, causing a reduction in the output power. If the passivation layer is not considered, simulations predict a nearly symmetrical behavior for positive and negative accelerations, with an optical sensitivity of 2.3 dB/g. Experimental and simulation confirm that passivation modes produce a reduction in the optical sensitivity for positive acceleration values, resulting in an asymmetrical response of the accelerometer.**

***Index Terms*—Acceleration measurement and silicon-on-insulator technology, antiresonant reflecting optical waveguides (ARROW).**

I. Introduction

OPTICAL accelerometers are very promising devices in the field of microoptoelectromechanical systems (MOEMS), since they overcome the drawbacks of electrical accelerometers: Their immunity against electromagnetic interference, together with the ability to have the emitter and the photodetector far from the accelerometer, i.e., connected through optical fibers, make them extremely useful in harsh environments, for example, in explosive atmospheres or where strong electromagnetic fields are applied. Among the integrated optics accelerometers, total internal reflection (TIR) waveguides with high refractive index (for example silicon nitride waveguides) in cantilever configuration are the most widely used due to their relative simplicity of fabrication [1]. However, silicon nitride generally suffers from high stress, causing the structure to deform or crack when its thickness is above 0.6 μm. Although this thickness allows the fabrication of TIR waveguides, if light is injected into a waveguide of these dimensions by end-fire coupling with a single-mode optical fiber, insertion losses are extremely high ($>$20 dB) due to the large difference between the optical fiber and waveguide cross sections. It is possible to obtain thicker waveguides by using other materials, as could be of silicon oxide, by varying the refractive index of each layer. However, this configuration requires thick buffer layers to prevent absorption from the silicon. Moreover, the mechanical stresses in such structures generally have the same sign, causing the cracking of the waveguide if the deposition conditions are not accurately controlled.

One possible solution is the use of antiresonant reflecting optical waveguides (ARROW) [2], which can overcome the inherent problems of high refractive index waveguides. Confinement in these structures is achieved by means of the high reflectivity of a Fabry–Pérot structure placed beneath the core while the confinement at the upper interface is provided by TIR. Lateral confinement is achieved by making a partial etch (rib) of the core. The interference cladding provides single-mode behavior of the waveguide at the working wavelength for a given core thickness. Furthermore, core dimensions can be made comparable with that of the input optical fibers, thus, allowing a large reduction of insertion losses.

ARROW structures have another significant advantage over high index TIR waveguides: the possibility of using cores with much lower refractive index than that of silicon nitride and subsequently much lower beam broadening. This point is especially important in the design of MOEMS, since frequently, a gap between the input and the output waveguides is present. Losses at this gap are function of the beam broadening and the gap length. Clearly, if the broadening is reduced, the gap can be enlarged, lowering the technological requirements. As compared with low-index TIR waveguides, the main advantage of ARROW structures arises from the fact that it is possible to choose the materials that conform the waveguide in such a way that the mechanical stresses in the structure are partially compensated.

II. Design and Simulation

On the basis of previous research performed with ARROW-A waveguides [3] intended for the visible range ($\lambda = 0.633$ μm), a new design for an optical accelerometer, as shown in Fig. 1, is proposed. It is based on a quad beam configuration [4] and consists on three waveguides: the input and output waveguides, placed on the chip frame, and a sensing waveguide located over the proof mass. There is a vertical displacement of the proof mass when a y-acceleration is applied to the accelerometer (throughout this letter, x and y will be the horizontal and vertical coordinates respectively, and z will stand for the propagation axis) and, therefore, a misalignment is produced

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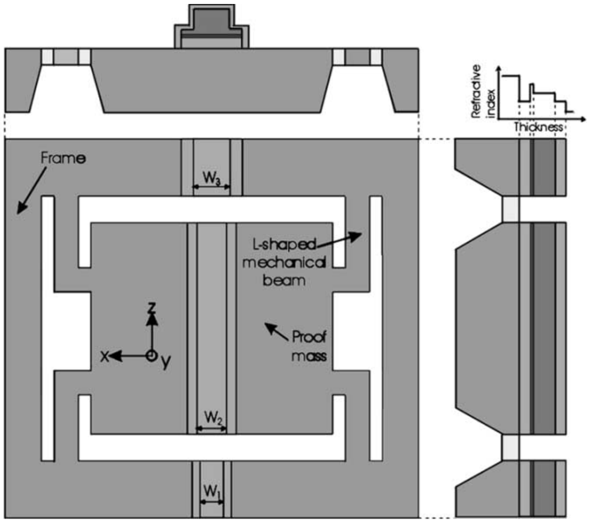

Fig. 1. Scheme of the misalignment-based optical accelerometer. $w_1 = 14$ μm, $w_2 = 30$ μm, and $w_3 = 50$ μm are the waveguide widths of an rib ARROW-A structure.

in both waveguide-to-waveguide transitions, causing a double increase in losses.

The impact in losses of light beam divergence in the x-axis has significantly reduced by progressively widening the waveguides employed ($w_1 = 14$ μm, $w_2 = 30$ μm, $w_3 = 50$ μm). However, it is not possible to compensate the light beam divergence in the y-axis. This point limits the maximum distance between all waveguides. In this case, this distance has been limited to 24 μm, large enough to assure the technological process repeatability in bulk micromachining in silicon. The sensing waveguide has been placed at the middle of the proof mass, as far as possible from the beams. Since the mechanical beams are only made of silicon, the proposed accelerometer is expected not to have a variation in its behavior due to thermally induced stress when submitted to temperature variations. It can also be observed that it has a self-test system: If the mass is broken, the configuration obtained corresponds to that of two waveguides separated by a distance slightly larger than the length of the proof mass, causing a large increase of the losses. The quad beam structure was chosen because it has higher natural frequencies (and therefore higher bandwidth) than the cantilever configuration for similar dimensions [5]. Moreover, in a quad beam design, due to the symmetry of the structure, the mass experiments a flat vertical displacement, which means that the waveguide placed on the proof mass will only be misaligned in the vertical direction. Finally, L-shaped external beams increase the mechanical sensitivity without causing a large increase in the accelerometer size.

Optical simulations have been performed using the nonuniform finite difference method [6], together with the beam propagation method [7]. The geometrical parameters of the quad beam accelerometer were optimized to achieve a mechanical sensitivity of 1 μm/g using the finite-element method (FEM) program ANSYS 5.7. Although this mechanical sensitivity could be considered too high (and, hence, the measured dynamic range too narrow), the reason for selecting this value is to have an easy-to-measure prototype. Clearly, larger values of acceleration could also be measured by making the mechanical beams stiffer.

TABLE I
MECHANICAL AND OPTICAL SENSITIVITY OF THE OPTICAL ACCELEROMETER

Accel.	Mech. sens. (μm/g)		Opt. sens. (dB/g) Without passiv.		Opt. sens. (dB/g) With passiv.	
	g>0	g<0	g>0	g<0	g>0	g<0
In y axis	1.050	1.050	2.23	2.25	1.84	1.55
In x axis	0.105	0.105	0	0	0	0
In z axis	0.202	0.202	0.31	0.34	0.15	0.11

As it can be observed in Table I, the highest optical sensitivity is due to displacements in the y-axis both with and without considering passivation, and this magnitude is much lower for the other two axes. The reason why the accelerometer is completely insensitive to x-accelerations is that the sensing waveguide is centered on the proof mass, and then, although an x-acceleration causes a mass displacement, there is no relative displacement of the center of the proof mass and, therefore, no misalignment between the waveguides. Concerning the self-test, optical simulations showed that losses should increase up to 12 dB when the seismic mass was broken and removed from the structure.

Mechanical simulations showed a simulated resonant frequency of 489 Hz.

III. Fabrication and Characterization

Accelerometers were fabricated on N type (100) oriented, 450-μm-thick bond and etch back silicon-on-insulator wafers from ShinEtsu [8]. The thickness of the buried silicon oxide was 2.0 μm and the thickness of the silicon layer was 15.0 μm. The ARROW structures were defined over these substrates, with the same technology as reported in [3]. At this point, all layers were removed from the wafer except in certain regions on the mass and the frame, where waveguides were to be located, assuring stress-free structures. Silicon anisotropic etching and SiO_2 wet etching at the backside of the wafer formed the proof mass. RIE on the front side defined the mechanical beams. At this point, a micromachined glass wafer (Pyrex #7740) was anodically bonded to the backside of the silicon wafer, to provide the accelerometers with higher mechanical stiffness. Measurements of the optical accelerometer were done by end-fire coupling.

It was observed that a small variation in the input fiber position could cause significant variation of the measured losses. Thus, a prepackaging was required. Input and output optical fibers were mounted on V-grooves made on silicon wafers with a glass wafer anodically bonded to it. Experimental results with this setup showed total losses of 18.5 dB, which were attributable to inadequate facet polishing, since the polishing of the glass–Si sandwich generally ends with tapered or rough facets.

Measurements were made with the accelerometer placed on a Ferris wheel with a controlled angular position: When the Ferris wheel was at 0°, the accelerometer was at 1 g, since the sensing axis of the accelerometer was that of the gravitational field. Increasing the angle caused a deviation of this axis, resulting in a decrease of the measured value of the applied gravitational field. The response obtained for the output power as a function of gravity is shown in Fig. 2, together with the simulations with and without considering the passivation effects. In this figure,

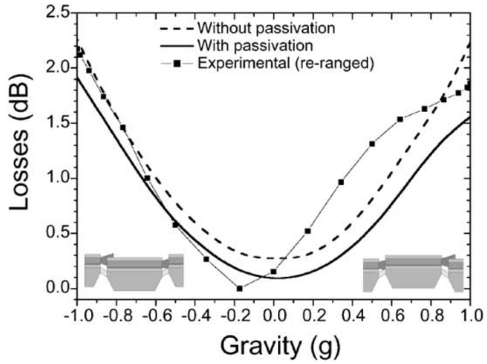

Fig. 2. Accelerometer losses as function of the gravity field: Simulated losses with and without passivation and experimental data, which has been re-ranged for comparison with simulations.

experimental losses have been re-ranged, fixing the minimum losses to zero. This has been done to confirm the behavior of the device. It can be observed that minimum losses are not obtained when 0 g is applied but are slightly displaced, corresponding to an offset misalignment of only 0.18 μm. It can also be seen that the accelerometer shows an asymmetrical response, with an optical sensitivity of 1.55 and 1.80 dB/g for positive and negative accelerations, respectively.

The explanation for this fact is the presence of a passivation layer over the core of the waveguide. When acceleration is positive, the proof mass displaces up, and light traveling by the sensing waveguide is injected into the passivation layer of the output waveguide, which guides it to the output multimode fiber in the same way as it happens in the cladding of optical fibers. This effect makes the output power higher then expected, producing the asymmetry in the accelerometer response.

On the other hand, if a negative acceleration makes the proof mass displace down, there is light injected into the passivation layer of the sensing waveguide, but this waveguide is long enough (4000 against 500 μm of the output and input waveguides) to make negligible the amount of power reaching its other end, because the roughness of the upper surface, the absence of bidimensional confinement on it, and the expectable presence of impurities on its outer surface will cause this kind of guided modes to present high absorption.

Obviously, if there was no passivation layer, all the power not injected into the core of the output waveguide would be lost, resulting in a symmetrical response. However, the elimination of that protection layer would make the packaging process much more delicate and the life of the device much shorter, so the presence of a passivation is highly recommended. One possible solution to this problem of asymmetry in the response of the device is to enlarge the output waveguide, in order that the amount of light guided by the passivation that reaches the output fiber could be negligible, as it happens in the sensing waveguide. Comparison between the simulated results with and without passivation confirms this latter discussion, which is also in agreement with measured experimental data.

For those applications where not only the magnitude but also the sign of the acceleration is required, the proposed configuration can be modified: Above -0.4 g, the output power as a function of the displacement can be considered as lineal. Then, by making an initial etch on the frames before defining the ARROW structures, the output power at 0 g can be selected to lay on this region, so it is possible to distinguish between positive and negative accelerations.

IV. Conclusion

An accelerometer based on rib-ARROW waveguides has been designed, fabricated, and characterized, demonstrating the viability of using ARROW structures in MOEMS. The mechanical elements have been designed as a quad beam structure with a proof mass and L-shaped beams to provide a flat misalignment between the waveguides located at the frame and on the proof when an acceleration is applied. The structure has been designed to have a mechanical sensitivity of 1 μm/g. Optical simulations have shown that a symmetrical response with 2.3 dB/g of sensitivity should be obtained in accelerometers without passivation. However, when the passivation is included, there exists a deviation of the symmetrical response that are due to the nonabsorbed passivation modes at the output waveguide. Good agreement with these predictions has been shown in the experimental results. The effect of the passivation modes can be overcame by making the output waveguides larger. Finally, the proposed configuration can be modified to work in the region above -0.4 g, where a highly lineal response of the output power as a function of the acceleration can be achieved.

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