Silicon Modulator Based on Mechanically-Active Anti-Reflection Layer with 1 Mbit/sec Capability for Fiber-in-the-Loop Applications

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***Abstract*—We present a micromechanical modulator for fiber-in-the-loop applications with projected optical bandwidths from 1.3 to 1.55 μm and data rates of several Mbits/sec. The device behaves as a damped oscillator. We have made a device with a ringing frequency of 1.1 MHz and a damping time constant of 1 μs. We indicate that with an appropriate linear filter the device could operate digitally with data rates of 1 Mbit/sec.**

FOR most near term local access fiber optic applications, upstream data rates (from the home to the central office) of a 100 kbits-few Mbits/sec may be adequate in many situations. In particular, as networks are installed it may be desirable to allow customers a reduced-cost option of simple audio or compressed video upstream data, with the possibility of later upgrade.

In [1] and [2], a system is described which converts CW portions of downstream light into upstream data. This is accomplished by tapping downstream light into a return fiber. Data is imprinted upon the return light by means of a light modulator, thus avoiding the use of a laser at the subscriber terminal. For very high return data rates (e.g., hundreds of Mbits/sec), a lithium niobate or semiconductor modulator is available yet costly. As mentioned above it is desirable to have a lower-cost, lower-performance option for the modulator. Note that this still allows high downstream data rates. We present here a modulator for this option, a micromechanical device fabricated on silicon using standard microelectronic techniques. Since this device operates surface-normal, tens of thousands may be fabricated on a wafer. In addition, the device requires only coarse lithography (2 micron linewidth rules would suffice). Thus the cost of the device (minus packaging costs) will be a few pennies.[1] The surface-normal mode of operation should also make fiber attachment inexpensive.

The device here is based on optical interference effects between a suspended, vertically moving membrane and the substrate. In Fig. 1 we show our device, which consists of a membrane supported by arms above an air gap. The air gap is created by complete undercut etching of a sacrificial layer. Similar micromechanical devices have been explored previously [3], [4], [5], but to our knowledge ours is the first device to employ a simple but powerful principle that allows high contrast without diffraction. That principle is essentially to fabricate a vertically-moving anti-reflection coating. This gives specific advantages to earlier devices. In [5] a Fabry-Perot modulator was made, in which the membrane comprised a multilayer mirror, the cavity was the air gap, and a second multilayer mirror was fabricated on the substrate to form a high finesse cavity. The drawbacks of this device are that it has a low optical bandwidth (~10 nm), and that precise control of the mirror reflectivity's must be achieved to null the cavity. Reference [4] presented a vertically-moving membrane with interference-induced modulation, but no particular design principle was applied so only low (~2:1) contrast was achieved. In [5], a vertically-moving grating was made, so that device switched between reflection and diffraction, so high contrast is

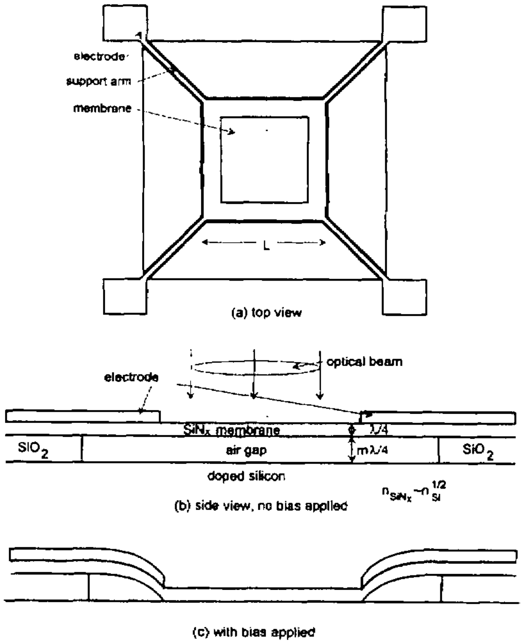

Fig. 1. Top (a) and undeflected (b) and deflected side views of our modulator.

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[1] Based on the costs of chips fabricated using the MOSIS foundry service, assuming an area per device of 100 × 200 microns, results in 13 cents per device. Wafer-scale costs should be less.

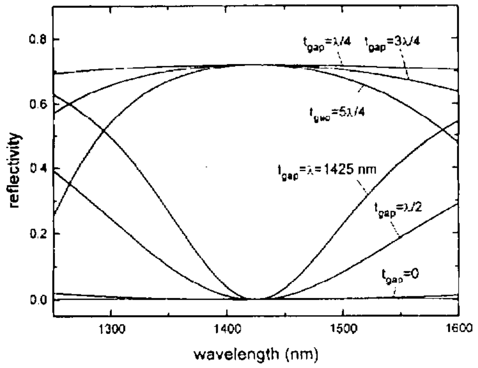

Fig. 2. Calculated spectra for different membrane positions.

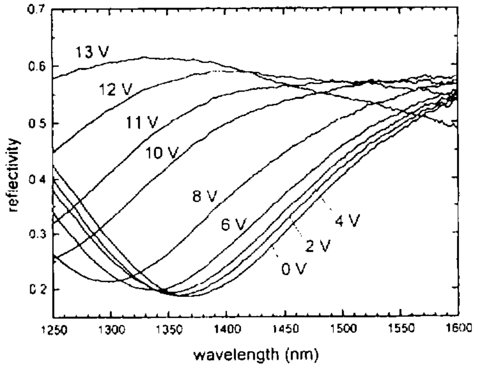

Fig. 3. Measured spectra of $L = 100$ μm device with $m = 4$ air gap. Etchant access holes (which were not required for small-area device) degrade contrast.

achieved only in the diffracted order, and has the wavelength dependence of a grating.

Our membrane may be fabricated out of plasma-enhanced chemical vapor deposition silicon nitride, whose refractive index may be controlled precisely in order to make it the square root of that of silicon (or the geometric mean of that of silicon and that of optical fiber, in the case where a fiber is attached) [6]. Thus when the membrane is brought into contact with the substrate (by means of electrostatic force resulting from bias applied between an electrode placed on the membrane and the doped substrate [Fig. 1]), an anti-reflection condition exists at a wavelength equal to four times the optical thickness of the membrane. This anti-reflection condition may extend over an enormous bandwidth, from 1.3 to 1.55 μm (Fig. 2). In Fig. 2, the index and thickness of the silicon nitride membrane are 1.87 and 1905 Å, respectively, so that its optical thickness is $\lambda/4$ at 1425 nm. Since its thickness is $\lambda/4$, when the air gap is also $\lambda/4$, the device forms a high reflectivity mirror (Fig. 2). In fact, for an air gap thickness of $m\lambda/4$, for m even an anti-reflection condition exists, and for m odd a high reflection exists, although the optical bandwidth decreases for $m > 1$. Hence we call the device the Mechanical Anti-Reflection Switch, or MARS device.

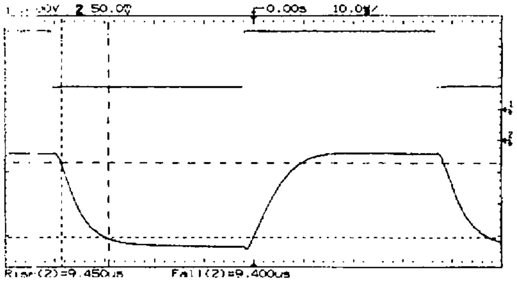

Fig. 4. Measured temporal response of $L = 100$ μm device to applied square wave in atmosphere.

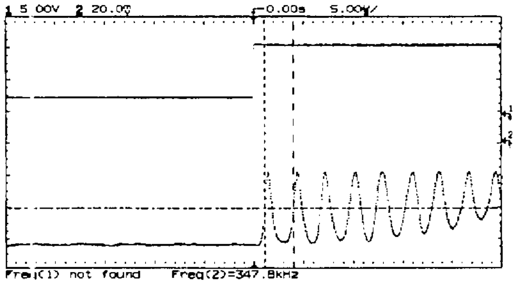

Fig. 5. Same as Fig. 4 in vacuum.

Here we present devices with $m > 1$, so that upon deflection through a quarter-wave there is still an air gap. This is beneficial in that possible sticking of the membrane to the substrate is avoided, but detrimental in that optical bandwidth is reduced. In addition, as we state below by going to $m = 1$ designs in the future drive voltage requirements should be greatly reduced.

A quarter wave-thick layer of poly-silicon may be added to the membrane under the SiNx layer (this is not demonstrated here). Since its index is that of the substrate, it does not affect the anti-reflection situation, and slightly increases the reflectivity in the reflecting state. This layer could add to the design flexibility of the device.

The device may easily handle the optical bandwidth requirements of fiber-in-the-loop applications. In addition it is cheap, has no polarization sensitivity, has wide fiber alignment tolerance, projected <1 dB insertion loss (with poly-Si layer) and >20 dB contrast, is chemically and mechanically robust, and requires no temperature stabilization. We first fabricated an $L = 100$ μm device with $m = 4$ (spectra shown in Fig. 3, note this large area required etchant access holes which degraded contrast). The device is fabricated by depositing a film of SiNx over a film of Al. A gold electrode is patterned over the SiNx, then openings in the SiNx are made. NaOH is then used to selectively remove the Al underneath the active device area. The shape of the final structure resembles a trampoline supported at the corners by arms. The electrode is patterned on the arms and around the rim of the "trampoline." The substrate's backside is contacted with silver paint. The temporal characteristics of this rather large device are shown

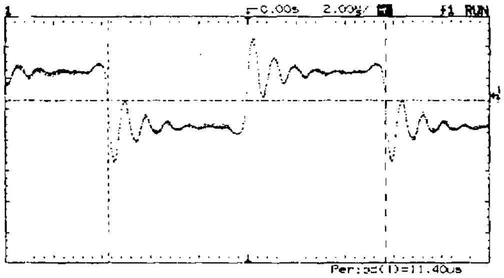

Fig. 6. Same as Fig. 4 for $L = 20$ μm device (in atmosphere).

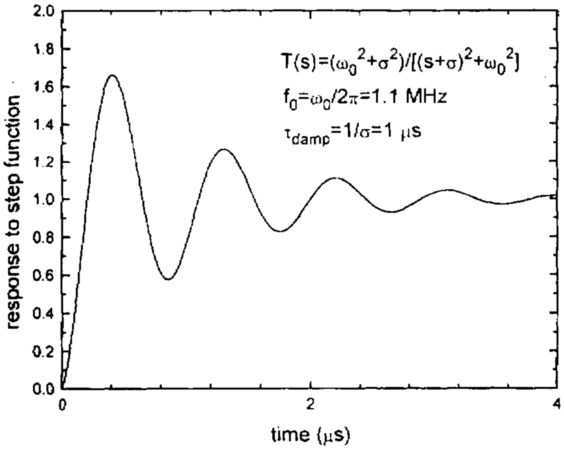

Fig. 7. Laplace transform model of reflection response of $L = 20$ μm device to voltage (inset), and associated response to step function. The agreement to the data is good. The device response rings at 1.1 MHz with a damping time constant of 1 μs.

in Fig. 4, using a 12 volt drive. The rise and fall times are about 10 μs. This is, in fact, already suitable for standard telephone service (POTS), even before scaling down in area. This device's speed is limited by air resistance, which is demonstrated in Fig. 5, where the device is operated under vacuum. The device rings in vacuum at its resonant frequency of 350 kHz, demonstrating that the device is a mechanical resonator overdamped by air resistance.

We then fabricated a scaled-down version of the device, with $m = 3$ and $L = 20$ μm. The support arms were 30 μm long and 5 μm wide. The contrast of the device was 13:1 at 1.52 μm. This lowered contrast compared to calculated values is probably due to not obtaining the design value for the SiNx film refractive index. For this smaller device, the voltage requirements increased to approximately 25 volts for $\lambda/4$ deflection. These voltage requirements should decrease greatly by going to $m = 1$. This is because the applied force for a given voltage goes as the inverse of the square of the air gap thickness (since both the capacitance and the electric field increase as the inverse of the gap). Therefore by going to $m = 1$ in future devices the voltage requirements should reduce by an order of magnitude.

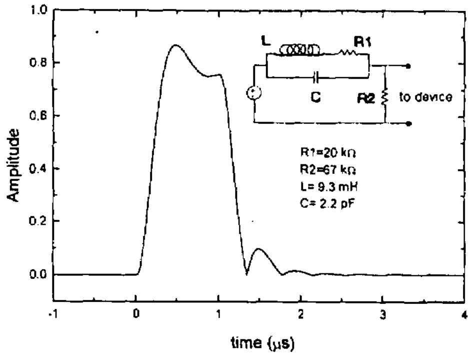

Fig. 8. Model of response of $L = 20$ μm device to 1 μs voltage pulse, using function of Fig. 6, with linear filter (inset) inserted between voltage source and device. The filter reduces the ringing, indicating that operation at 1 Mbit/sec is possible.

The temporal response of the $L = 20$ μm device to an applied square wave is shown in Fig. 6 (in atmosphere). The device is now underdamped. The rise time has decreased to 250 ns, but it overshoots and rings. A Laplace transfer function relating reflectivity to applied bias is given in Fig. 7, and it models the measured response well. It has a single pole at 1.1 MHz and a damping time constant of 1 μs. An appropriate filter inserted between the voltage source and the device should allow operation without ringing. This is shown in Fig. 8, with the associated calculated response to a single 1 μs long voltage pulse. The absence of ringing in the pulse indicates that digital operation at 1 Mbit/sec is possible.

In conclusion, we present a micromechanical modulator for fiber-in-the-loop applications with projected optical bandwidths from 1.3 to 1.55 μm and data rates of several Mbits/sec. The device behaves as a damped oscillator. We have made a device with a ringing frequency of 1.1 MHz and a damping time constant of 1 μs. We indicate that with an appropriate linear filter the device could operate digitally with data rates of 1 Mbit/sec.

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