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The Integration of Advanced Photonics and MEMS LDRD 26519 Final Report

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Abstract

In this work we have demonstrated the fabrication of two different classes of devices which demonstrate the integration of simple MEMS structures with photonics structures. In the first class of device a suspended, movable Si waveguide was designed and fabricated. This waveguide was designed to be able to be actuated so that it could be brought into close proximity to a ring resonator or similar structure. In the course of this work we also designed a technique to improve the input coupling to the waveguide. While these structures were successfully fabricated, post fabrication and testing involved a significant amount of manipulation of the devices and due to their relatively flimsy nature our structures could not readily survive this extra handling. As a result we redesigned our devices so that instead of moving the waveguides themselves we moved a much smaller optical element into close proximity to the waveguides. Using this approach it was also possible to fabricate a much larger array of actively switched photonic devices: switches, ring resonators, couplers (which act as switches or splitters) and attenuators. We successfully fabricated all these structures and were able to successfully demonstrate splitters, switches and attenuators. The quality of the SiN waveguides fabricated in this work were found to be qualitatively compatible to those made using semiconductor materials.

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The authors gratefully acknowledge Sandia National Laboratories Microelectronics Development Laboratory (MDL) especially the efforts of Melanie Tuck. The authors also acknowledge Jim Bur for his work in preparing and testing the samples.

Executive Summary

There is considerable interest in optical MEMS. However, such devices typically do not take advantage of the full range of possibilities that arise from the wave nature of light. Typically these devices consist of conceptually simple, but structurally complex, mechanical systems, which are really just movable mirrors. On the other hand photonics devices are typically structurally simple, they rarely have more than a single level, but offer "complex" photonics functionality. One potentially interesting area of photonics research is that of ring resonators and waveguide couplers. Physically these are simple structures, but they have the potential of being able to act as narrow, high efficiency band filters/drops and couplers. Progress in this area has been hindered by fabrication difficulties and difficulties in switching. The application of MEMS to this area potentially solves both problems. What is more, the size scale of such devices is almost ideal for MEMS; small displacements, on the micron range, give rise to large changes in optical properties. Perhaps due to relatively recent rapid progress in fields that traditionally have not overlapped, there exists a window of opportunity to combine elements of the two fields to make significant technological advances. MEMS can offer to advanced photonics a simple, manufacturable "switch". On the other hand, advanced photonics offers the ability to not just reflect light in free space, but to confine light within waveguides where it can be efficiently manipulated, switched, and filtered. This added functionality can not be realized by current MEMS technology.

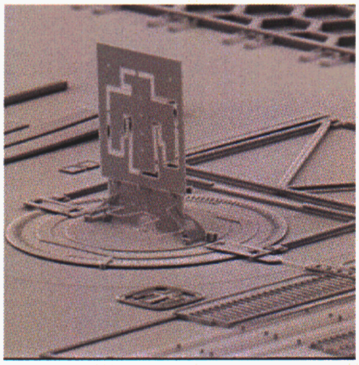
We have demonstrated the fabrication of two different classes of devices which demonstrate this principle. In the first class of device a suspended, movable Si waveguide was designed and fabricated. This waveguide was designed to be able to be actuated so that it could be brought into close proximity to a ring resonator or similar structure. In the course of this work we also designed a technique to improve the input coupling to the waveguide. While these structures were successfully fabricated, post fabrication and testing involved a significant amount of manipulation of the devices and due to their relatively flimsy nature our structures could not readily survive this extra handling. As a result we redesigned our devices so that instead of moving the waveguides themselves we moved a much smaller optical element into close proximity to the waveguides. Using this approach it was also possible to fabricate a much larger array of actively switched photonic devices: switches, ring resonators, couplers (which act as switches or splitters) and attenuators. We successfully fabricated all these structures and were able to successfully demonstrate splitters, switches and attenuators. The quality of the SiN waveguides fabricated in this work were found to be qualitatively compatible to those made using semiconductor materials.

In summary in the course of this work we were able to demonstrate that the premise behind this work was correct, that it is in fact possible to fabricate relatively simple MEMS actuators integrated with simple, but highly functional photonics devices to give a mechanically functional system with a high level of photonics functionality.

Introduction

There is great commercial and DP interest in optical MEMS. However, the MEMS devices of most interest at present do not take advantage of the full range of possibilities that arise from the wave nature of light. These devices typically consist of conceptually simple, but structurally complex, mechanical systems, which are really just movable mirrors, Fig. 1(a,b). The major potential application for such systems is in structurally complex optical switching networks in which optical signals propagate in free space. Once perfected, such systems have the capability to strongly impact the optical communications industry, and this accounts for the high level of commercial interest in this area. However, these systems are not expected to be the final embodiment of optical communications routing systems. There exists a strong motivation to add functionality and shrink dimensions. Neither of these ultimate goals can be achieved with the current state-of-the-art tilting mirror systems either fielded or proposed. In order to attain this next level of functionality it will be necessary to more fully exploit the properties of light with arise from its wave nature. In order to attain the desired levels of miniaturization it will be necessary to confine and manipulate light in waveguides. This LDRD addressed these goals by exploiting recent advances in the areas of MEMS and advanced photonics. This philosophy is schematically shown in Fig. 2.

Advances in photonics have lead to the demonstration of potentially interesting structures; one potentially very interesting area of research is that of ring resonators and waveguide couplers [1-5]. Physically these are relatively simple structures, but they have the potential of being able to act as narrow, high efficiency band filters/drops, Fig. 2-3, and couplers. In a general sense these devices arise from the coupling between light confined within a waveguide and a well-defined ring, disc, or waveguide segment. Wavelengths, which can resonate within the ring or disc are dropped from the waveguide and can be coupled in turn into another separate waveguide. In the case of couplers, when two sections of waveguide are brought into close enough proximity, light will partition itself between the two waveguides, depending upon the length of the overlap. Under optimal conditions, the light can be switched between waveguides with very high efficiency. This is a level of functionality that is completely unattainable with mirror switching systems.
This is graphically illustrated in Fig. 3-4.



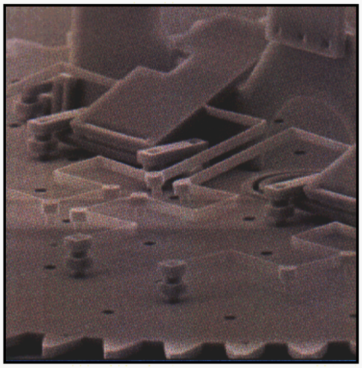


Fig. 1(a,b). Example of the level of complexity currently achievable by Si MEMS.

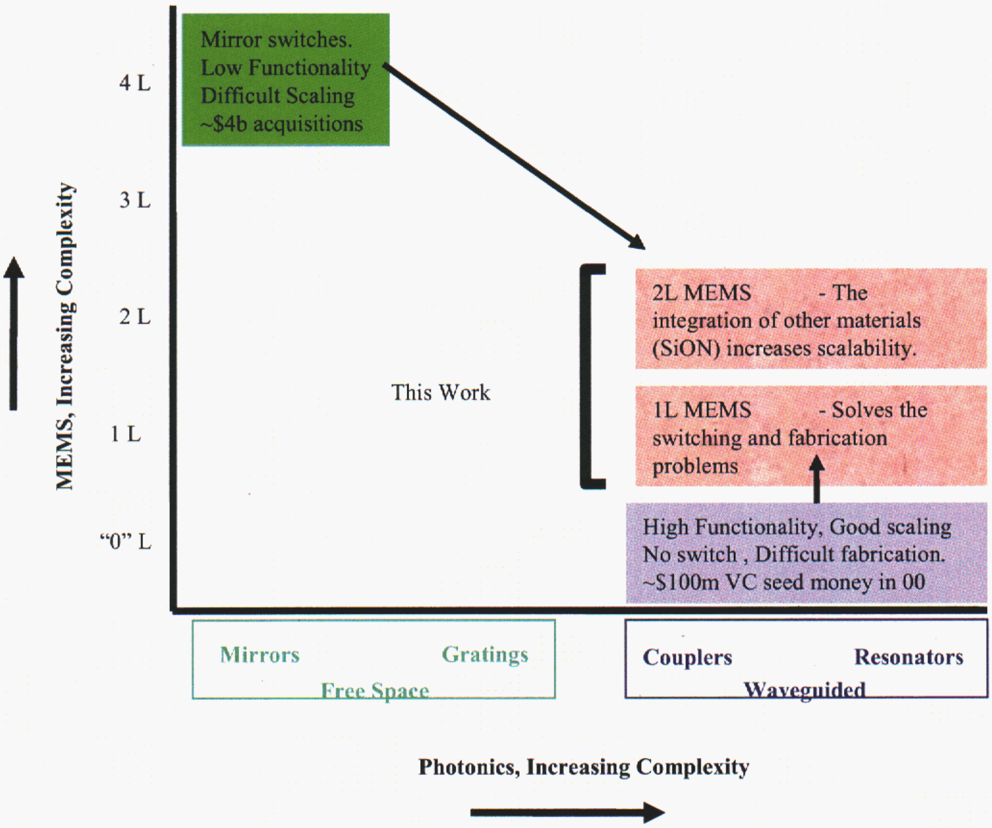


Fig. 2.
Showing a graphical representation of the motivation behind this work.

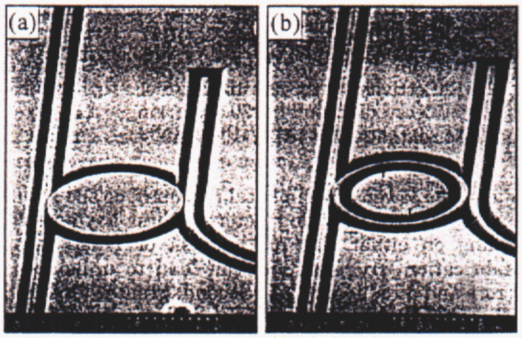


Fig. 2. SEM images of a 10.5-μm-diameter (a) disk and (b) ring.

Fig 3.
SEM images of disc and ring resonators. Though static devices have been demonstrated by various groups, the small (~100nm) spacing between the waveguide and resonator is a problem. Also switching has not yet been reported. (From [1])

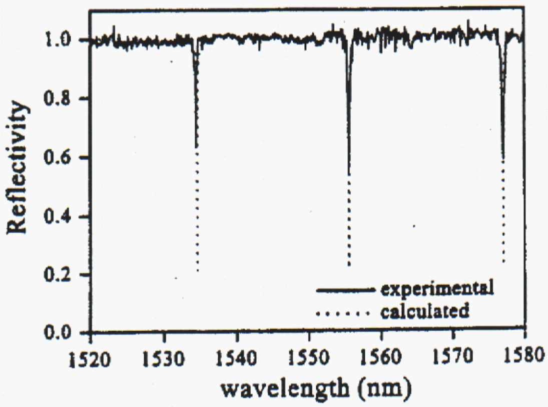


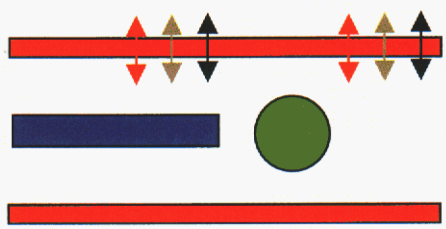
Fig. 3. Measured (experimental) and calculated reflectivity, showing resonances from a 10.5-μm disk with 2% coupling and $\alpha = 1.6$/cm.

Fig 4.
Spectra obtained from one of the devices shown in Fig. 3. The resonant wavelengths are dropped from one waveguide to the other. This functionality is of critical importance to optical communications applications, and is unattainable using standard MEMS technologies. (From [1])

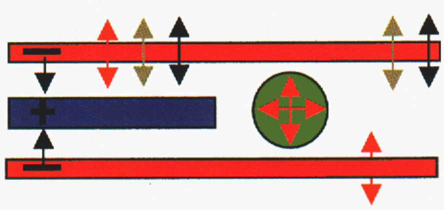
However, despite a flurry of recent work in this area, this field suffers from 2 major shortcomings, fabrication difficulties and the lack of a switch. These devices are typically fabricated in high index materials. This results in a high level of confinement and enables tight waveguide bends, and eventually a high density of photonic "circuits". However, this tight confinement in turn means that in order to couple into the resonator or coupler, the waveguide must be separated by less than 100nm from the structure. This is an extremely difficult dimension to maintain and results in a large variability in the most sensitive and important part of the device. The other limitation of these devices is the current lack of a switch. In this LDRD proposal we proposed to address both of these shortcomings by integrating these photonic devices with MEMS.

Single Crystalline Silicon Devices with Moving Waveguides

While photonics structures have typically been fabricated in the III-V systems, they have also been demonstrated using Si, the major MEMS structural material. Single crystalline silicon is low loss and its high index should enable a high density of photonic circuitry [6-7]. Using MEMS it should be possible to, very reproducibly and accurately, move a section of waveguide into proximity to another component such as a ring resonator or coupler. Since the waveguide is now fabricated well away from the other component, the complications, which arise from the 100nm gap, no longer exist and switching is the result of a physical translation enabled by the MEMS actuator. What is more, the small ~1-2 micron displacements involved are ideally suited to MEMS applications. This means that simple MEMS actuators can be used and in this case a simple single crystalline Si actuator can be easily integrated with a single crystalline silicon waveguide all on the same level, Fig. 5. MEMS actuated switching will never be extremely fast; however, the 1-100 microsecond switching times expected for such a small displacement are more than sufficient for many applications.



Resting state



Actuated state

Figure 5.
Schematic representation of a MEMS actuated drop filter. In the resting state the waveguides are sufficiently separated from the disc resonator that there is no coupling between the light and the resonator. In the actuated state a potential is applied which physically pulls the waveguides into close proximity to the disc. Light, which is of the correct wavelength will resonant in the disc and be dropped to the second waveguide. The resonant linewidth has been demonstrate to be less than 0.2 nm in static devices. The relatively small displacements involved are ideal for MEMS applications allowing the implementation of the simple parallel plate actuator shown schematically.

While it seems likely that single crystalline silicon may be sufficient for many applications, we also proposed to investigate the integration of other waveguide materials, such as silicon oxynitrides, with Si based MEMS structures. These materials systems offer the advantage of very low losses and due to the relative simplicity of the MEMS actuators required, integration with Si MEMS should be possible. As will be seen below this is the eventual direction we ended up in taking.

Coupling between the waveguide and the active structures is critical in these applications. We initially addressed this by optimizing the process flow so that for example, all critical dimensions are on the same mask level to eliminate variations in level-to-level tolerance.

We also believe that it may be possible to compensate for some level of process variation through a much higher level of continuous control of separation offered by MEMS. For example, to first order, the coupling of waveguides is mostly affected by the length over which they are in close proximity and this length will be subject to some level of uncontrollable process variation. However, the coupling is also dependent upon the physical separation and MEMS actuation offers use a very high level of control over this parameter that may enable us to compensate for a lack of process control.

Work in FY 01 concentrated on the investigation of Si structures in which simple MEMS actuators are integrated with photonics components such as ring resonators and couplers. This involved the design of the Si waveguides, actuators and optical elements. Proof of concept parts were fabricated in poly-crystalline silicon. While optically lossy, polysilicon is "cheap" and readily manipulated. Once proof of concept was demonstrated in this system the optimized designs were transferred to the more expensive and less flexible SOI substrates.

In this initial work, we designed 2 level test structures with waveguides, and resonator and coupler switches. The structures were designed to be switched with a parallel plate-type switch. The narrow portion of the waveguide, in which the light couples to the resonator or coupler, is supported by a thicker strut. To aid coupling of light into the waveguide, the waveguide tapers out in stages from the active 0.2 micron wide active area to 6 microns at the input side. The actuator and electrode portions are designed to have a gradient in fill factor to allow for CMP (Chemical-Mechanical-Polishing) dishing to create thin ~0.5 micron high active region while retaining a thicker ~1.5 micron thicker input coupling region. This will be discussed in more detail later. Resonator rings are supported off the substrate by silicon nitride posts. The design and process flow was first tested out in polysilicon. Using these test lots we demonstrated silicon nitride pillar/anchor formation, narrowing down of the active portion of the waveguide, CMP dishing, polishing of end facets, release of the parts by supercritical CO2 drying and electrical actuation. Due to the long led time of non-standard SOI material we had thought that it would not be possible to obtain single crystalline structures until the second year of the LDRD. However, we were able to obtain existing SOI material. Parts fabricated using this material were completed through the fab in the first year. Since it is well known that single crystalline silicon has better optical properties than polysilicon we tried to perform optical testing on these structure and not the polysilicon structures. Initial tests on these structures seemed to indicate functionality. MEMS actuation of the structures was observed at between 5 and 10 volts. This low actuation voltage is due to the relatively flimsy nature of the waveguide. This also requires a supercritical CO2 release to avoid stiction of the waveguides to the substrate. An SEM image of one of these completed structures showing it's component parts is shown in Fig. 6.

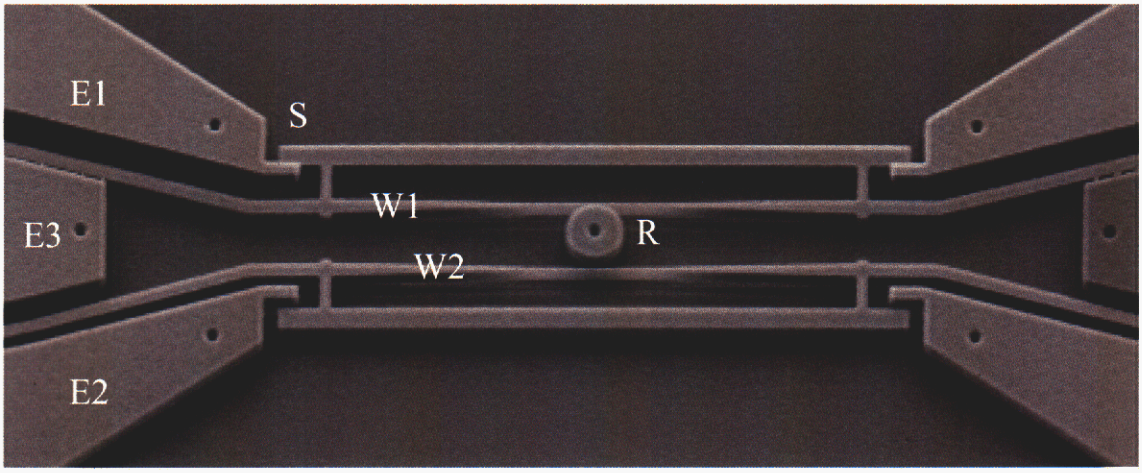


Figure 6.

Slightly angled top view of a resonator structure. The part has been released in HF only and as a result the waveguides (W1, W2) are stuck to the substrate. This can be avoided with supercritical CO2 drying. Parts which are not stuck tend to charge, decreasing the SEM resolution. The relatively narrow waveguides have been completely released from the substrate and are connected electrically and mechanically to the electrodes E1 and E2. When a potential is applied between electrode E3 and E1 (E2) there is a force of attraction, which pulls the waveguide closer to the ring (disc) resonator R. The distance of motion is controlled by a stop S, which is at the same potential as the waveguide. Motion stops when the strut comes into contact with the tab on the electrode. Both waveguides can be actuated independently. The other purpose of the strut is to strengthen the narrowed region of the waveguide. In the vicinity of the resonator (R), the waveguide is ~0.3 microns wide. The resonator and ends of the electrodes are attached to the substrate by electrically isolated posts, (small black dots). The electrodes taper out in order to create a gradual variation in percent silicon which is used to create a vertical taper to the waveguides as will be discussed in more detail below.

Used of CMP to Improve Input Coupling

One of the major problems in integrated optics is the coupling of light from fibers into the waveguides of the integrated optics system. Waveguides can readily be tapered in the plane of the substrate, but improved coupling vertically is a challenge. In this part of the project we developed CMP processes which result in the gradual transition from a thick input waveguide section to a thin active region. We achieved this by taking advantage of a process known as dishing which occurs during chemical mechanical polishing. To first order, the polishing rate is proportional to the product of the local pressure and the pad velocity. The local pressure is inversely related to local average exposed area. Since the polishing process has a relatively long interaction length there is a naturally smooth transition between regions, Fig 7. The resulting surface finish is very fine. By introducing a gradual variation in exposed area it is therefore possible to create a gradual taper. This is done without the addition of any extra photolithography steps. The SOI material we had available to us was only 1.5 microns thick, while the target for the active region of the device is 0.5 microns. Thus the maximum possible ratio between input and active region is something less than 3:1since there is always a finite amount of CMP removal regardless of fill factor. To date we have demonstrated a taper from 1.0 microns to 0.5 microns, Fig. 7. Another important variable to control is the thickness of the active region of the device. We were able to achieve this by taking advantage of differing CMP rates between materials and effective changes in exposed area. By depositing an oxide film of the desired thickness after etching the silicon, but before CMP, it is possible to control the final thickness. If the deposited film is silicon dioxide and the CMP slurry is formulated to have a high selectivity to silicon dioxide versus silicon, then the polishing process will slow greatly once the surface reaches the top of the oxide. There is also a geometric effect by which the percent of loading effectively goes to 100% once the level of the oxide is reached. The deposited film also serves to strengthen the thinned portions of the waveguide and this allows them to survive the CMP process.

The use of SOI allowed us to greatly smooth the surfaces of the waveguides. This is critically important since due to the very high index contrast between silicon and air scattering of light at surface imperfections is expected to be a major loss mechanism. Single crystalline material eliminates the grain boundaries which become decorated during the HF release step and allows for the use of a oxidation process to eliminate some of the sidewall roughness. The 200nm oxidation used resulted in the effectively isotropic consumption of ~100nm of silicon from the sidewalls. Simple geometric considerations predict that this should be effective in greatly reducing the amplitude of roughness with pitches up to at least 100nm which is roughly that of the sidewall "ripple" observed after etch of these structures. AFM has not yet been performed, but SEM clearly shows a reduction in roughness.

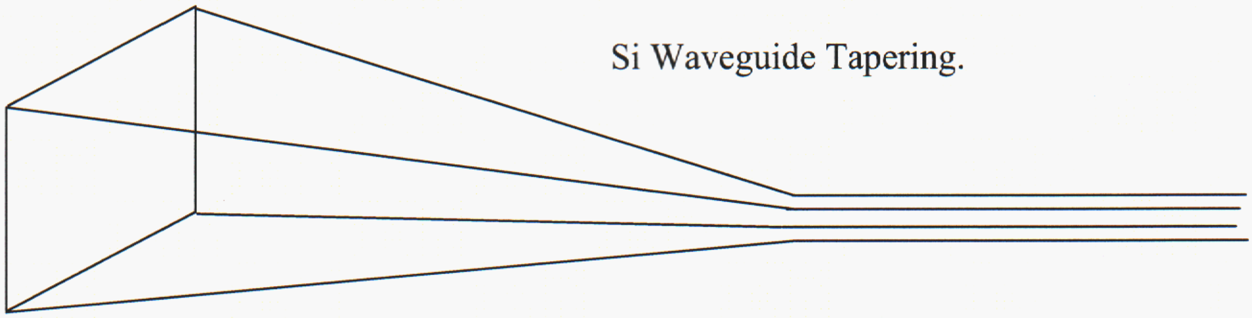
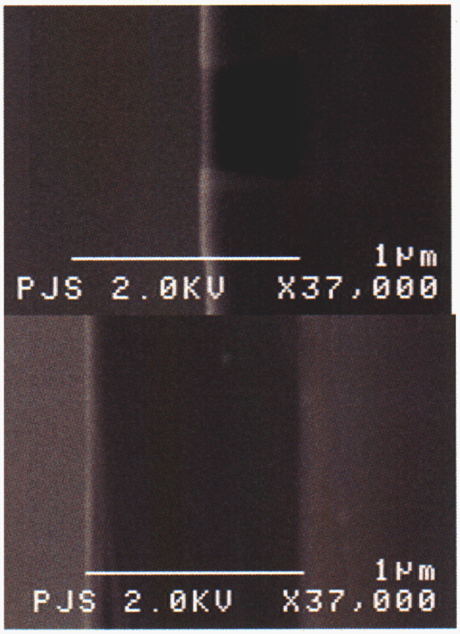


Fig 7.
Taper in X-Y the result of photopatterning. Taper in Z the result of Chemical Mechanical Polishing (CMP) dishing. CMP taper expected be very gradual and "rounded", CMP planarization lengths ~1mm.

Figure 8.
The effect of CMP dishing, the image on the left shows the thickness of the waveguide in the active region of the device. The fill fraction of silicon is low, <10%, in this region and roughly 1 micron of Si has been removed (initial thickness was 1.5 micron). On the other hand only 0.5 micron of material has been removed from the input section of the guide where the fill fraction was >90%.



However, the relatively flimsy structures were not able to readily survive the relatively harsh processing required to polish the input and output facets and mount them into the optical test bench. As a result we were forced to consider a redesign employing a different far more robust configuration. This approach will be described below and was ultimately found to be successful.

SiN Waveguided, Vertically Actuated, Structures

During testing of these Si based devices we found them to be too fragile to survive reasonable testing and processing, such as grinding end faces to improve input coupling. As a result, we have moved on to dielectric waveguides integrated with a vertically actuated W plate onto which was attached various optical elements, Fig 8. This configuration is far more robust and offers a higher level of functionality. A novel fabrication process was developed to realize these structures. It involves SiN based waveguides with a silicon dioxide lower cladding [8], a polysilicon sacrificial layer and a W actuation plate. Mechanically, the design is stable through its range of motion with actuation voltages between 10 and 100 volts, depending on the function targeted. It should be quite possible to lower the actuation voltage. The structures are currently stiff enough to allow air drying and we have observed no incidences of stiction during actuation. In the actuated state, these electrostatically based structures consume almost no power. The design allows for a continuous range of optical coupling. A wide variety of devices were laid out and fabricated in the same process flow. These include three types of broadband switch, splitters based on couplers, attenuators based on adsorption by a metal plate, and narrow band switches based on ring resonators. The broadband switch, attenuator, and the splitter have been demonstrated to work experimentally. The ring resonator-based narrow band switch has been fabricated and tested mechanically, but not yet optically. A schematic of the fabrication process is shown in Fig. 9 and outlines of the different optical elements fabricated is given in Fig. 10.

A TA was also filed on this work.

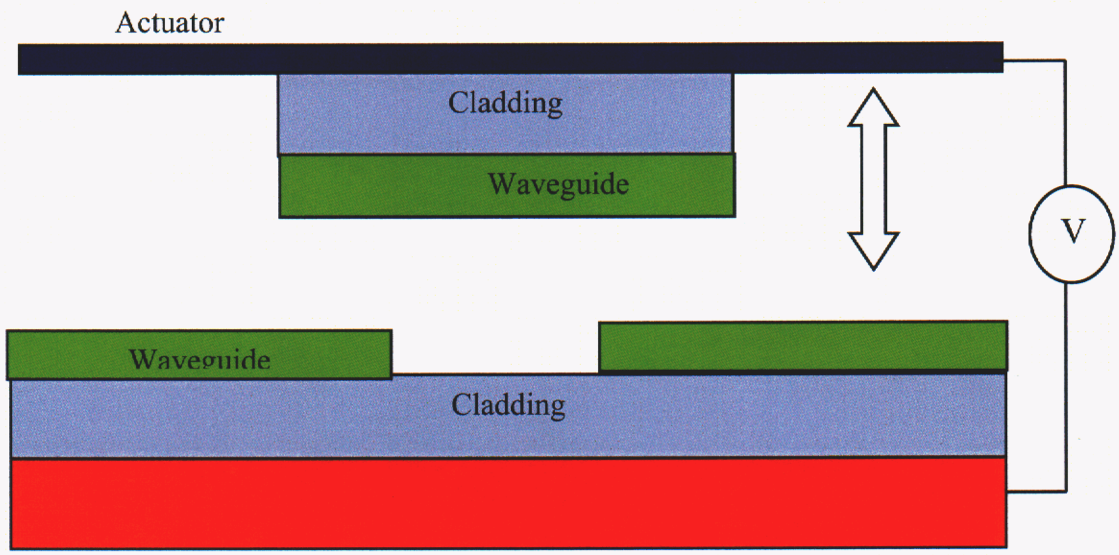
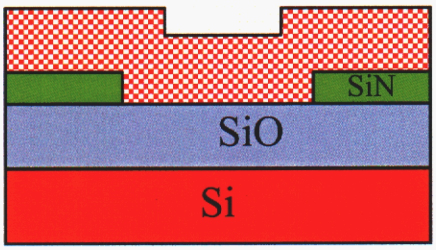
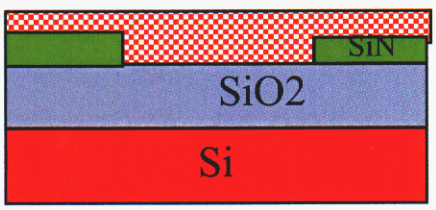


Fig. 9 Schematic Process flow

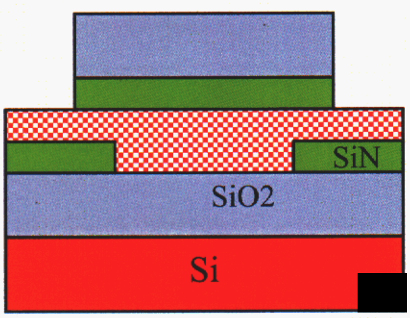
Grow 2 micron silicon dioxide lower cladding. Deposit silicon nitride and pattern lower waveguides.



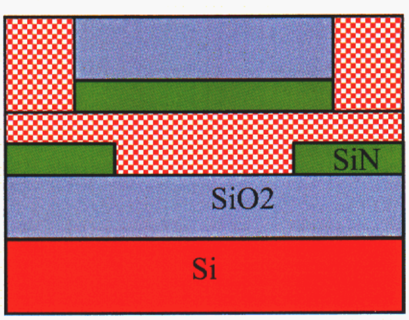
Deposit sacrificial polysilicon.



Planarize polysilicon.

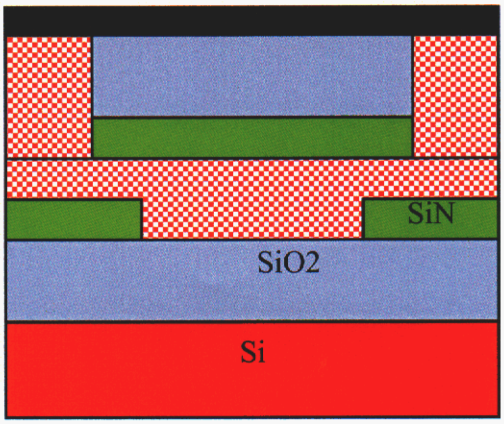


Deposit SiN waveguide oxide cladding. Pattern SiN and oxide.

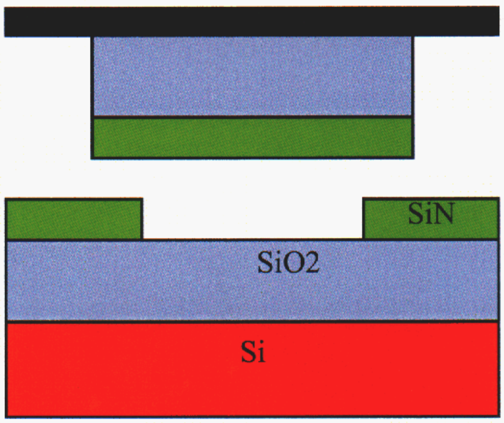


Deposit polysilicon and CMP planar.

Fig. 9, Schematic Process flow con't.



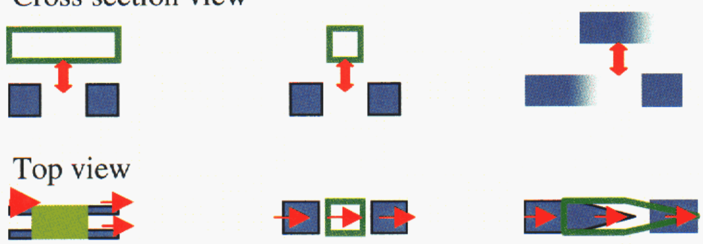
Deposit and pattern tungsten actuator.



Remove sacrificial polysilicon with KOH. The KOH etch will not attach the W or the SiN and only very slowly attacks the oxide cladding.

Figure 10
Schematic representations of the different structures investigated. They consisted of various broadband switches, a coupler, which acted as either a splitter or a switch. A narrow band switch in the form of a ring resonator, and an attenuator. Attenuators are needed to equalize the power being propagated at each wavelength.

Cross section view

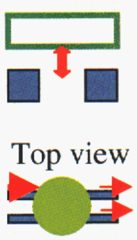


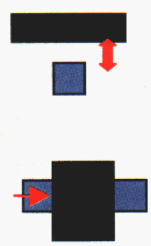
Coupler.
Top segment is moved down to increase coupling between two waveguide. Switches and splits.

Switch.
Short segment translated downwards to fill gap between two waveguide segments.

Switch:
Light is gradually coupled into a vertical segment due to a taper. Light is then coupled back down using another taper.

Cross section view





Resonator.
Top segment is moved down to couple with the two waveguides. Wavelengths that can resonate in resonator are dropped to second waveguide.

Attenuator.
A slab of metal actuator is pulled into proximity to the waveguide. Light evanescently couples from the waveguide and is adsorbed. Level of attenuation depends on closeness of approach.

The fab run used to create these parts was JF30901A. The first run of this product yielded working parts. Wafers pulled from early in the process were also used in splits. Figure 11 shows images of different devices fabricated in the course of this work.

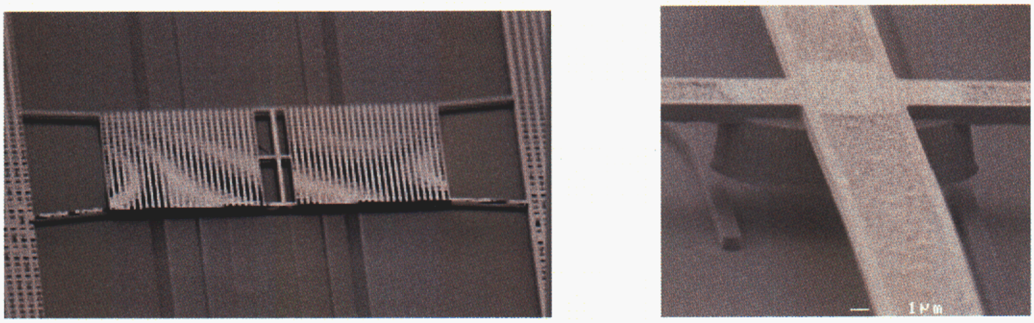


Fig 11.
SEM micrographs showing the suspended metal plate on the left and a blowup of the ring and waveguide structure on the right. The plate is W and is anchored to the pads on either side. The counter electrode is the substrate silicon. The ring on the right can be brought closer to the waveguides by applying a bias between the substrate and the plate. In the micrograph on the right, the SiN ring with its top cladding can be seen along with the waveguides and the support arm of the W plate. When the ring is pulled into close proximity to the waveguides, light that can resonant in the ring will be dropped to the other guide. This level of functionality is not possible with standard MEMS.

Testing

Mechanically the structures were found to actuate at voltages ranging from 10-100 V. In this voltage range it was possible to demonstrate splitting, switching and attenuation. While the voltages are high for CMOS drivers these systems draw very little current and therefore consume very little power.

For optical testing a wavelength of 1.5 microns was chosen. The reason for this is that this is the major long line optical communication wavelength. However, it is important to keep in mind that the waveguides are capable of propagating light all the way into the visible, though the waveguide size for single mode operation will vary, as will the size of the photonic components. The size of the waveguides used in the active regions of the waveguides was ~0.5 x 1.2 microns. However in order to facilitate the coupling of light into the waveguides the width of the waveguides at the input was ~6 microns. These wider guides were multimode. There was a 1000 micron long adiabatic taper region between the wider input and smaller active regions of the waveguides. Waveguides with widths of 6 and 20 microns were also laid out, they were used to help with the alignment of the output of the laser to the input of the active regions of the device.

The waveguides were found to work well, the loss was not measured quantitively, but qualitatively it was found to be on the same order or better than that of the III-V ridge waveguides investigated with the same system. The narrower waveguides were found to be single mode as expected while the 6 micron input guides were found to be multimode, also as expected.

Testing was successful on the coupling structures and the attenuator structures. A schematic of the design of the coupling structures is given in Fig. 12

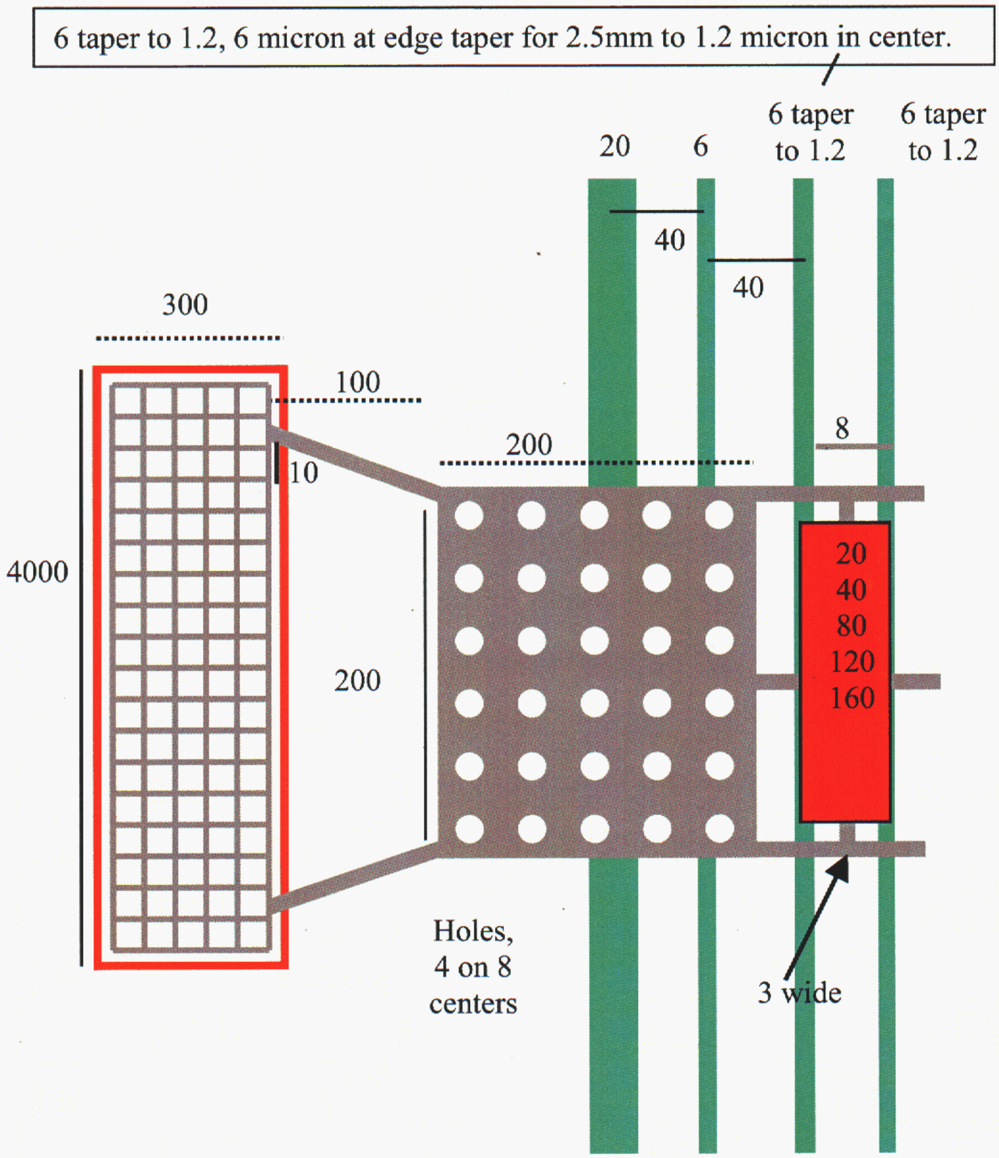


Fig. 12
Outline of the design of the coupling structures. The design is symmetrical about a line through the middle of the coupler, (red rectangle). In order to save space only the left hand side of the structure is shown. The 40 micron long coupler was found to work well.

The coupler is schematically shown in Fig. 12 which shows the left hand side of the device which is symmetric about a line through a line down the middle of the coupler.

The edges of the coupler are aligned with the edges of the waveguides on either side which were separated one from the other by a distance of 8 microns. The coupler was nominally 1.4 microns above the waveguides, Fig. 13.

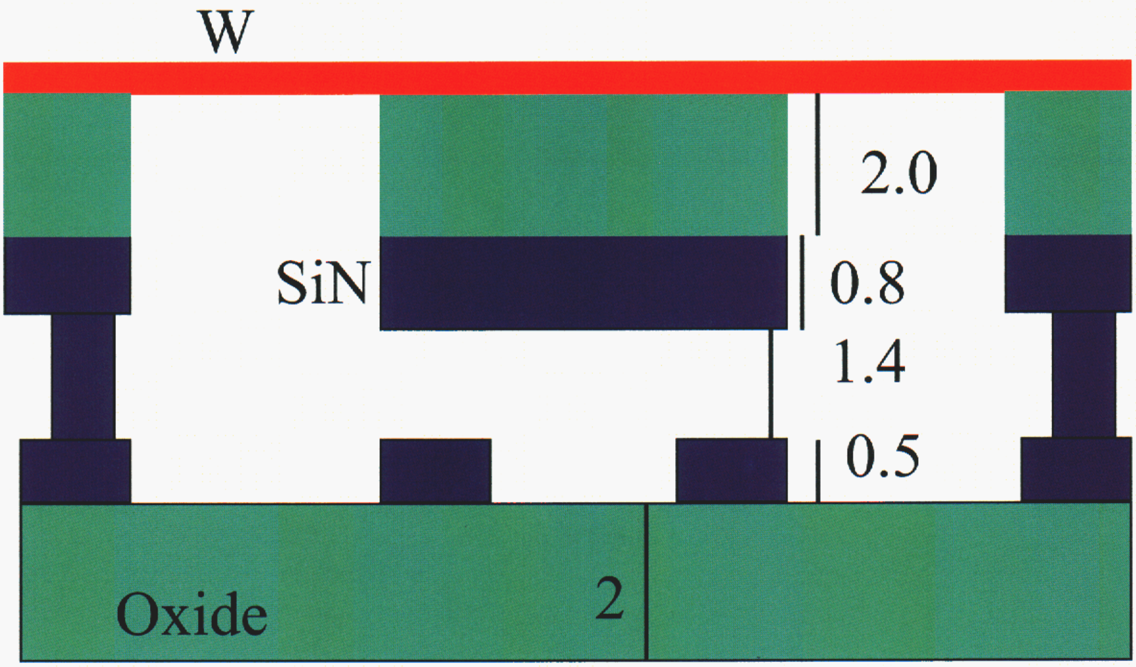


Figure 13.

Schematic cross section view of the structures, the blue color is SiN, waveguides and structural material, the green is the oxide cladding and the red is the W actuator.

When a potential is applied between the W actuator and the substrate the SiN coupler moves closer to the waveguides. This changes the effective index between the waveguides. Changing the effective index in turn changes the level of coupling between the waveguides. As the coupling is increased the light begins to partition itself between the two waveguides. By controlling the degree of coupling it is possible to move the light from one wavelength to the point where it is split between the waveguides and finally to the point where it is now completely contained in the second waveguide. This behavior is demonstrated experimentally in Fig. 14.

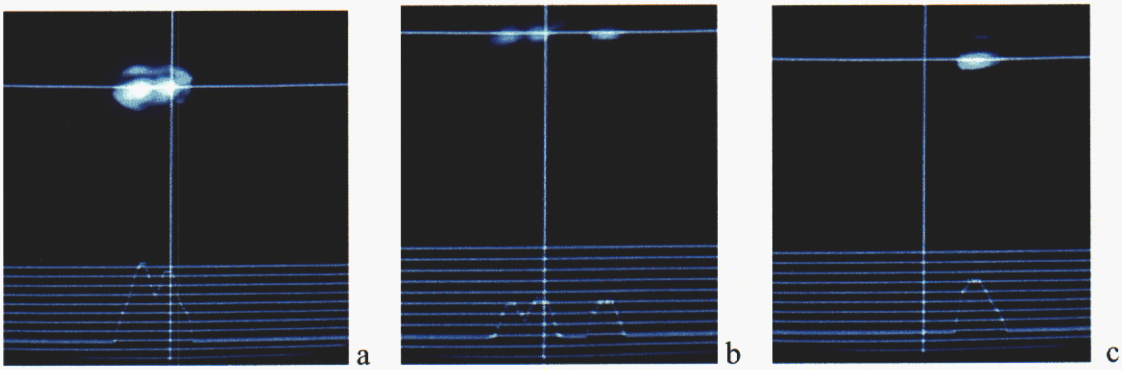


Fig. 14.
Experimental demonstration of splitting (b) and switching (a,c) in a coupler configuration, schematically shown in Fig 1, second from the left. The initial transmitted beam is shown in (a). The width of the input waveguide resulted in multimode operation, However, it was easier to couple into this larger waveguide. As the voltage is increased a block of SiN is brought into proximity to the region between two waveguides. This increases the coupling between the two guides and some of the light now is propagating in both waveguides (b). As the voltage is increased further all of the light couples into the second guide (c).

In this experiment the input beam was 6 microns wide at its input and output, the waveguide is single mode in the coupling area. However, the waveguide is initially multimode (a). This is not a serious problem. As the coupler section is brought closer to the waveguides the coupling between the waveguides is increased and light is now split between the two waveguides (b). As the coupling is increased further all of the light is now propagating in the second waveguide (c). Couplers are well understood, however they are typically static structures [ ]. This level of functionality, switching and continuously splitting in a relatively small waveguided area is novel.

Another type of structure of interest for telecommunications is an attenuator. Attenuators are used to reduce the power propagating in certain wavelengths in order of equilibrate the power propagating in each wavelength. When optical signals consisting of a range of wavelengths are amplified, the wavelengths with the highest power initially are amplified more. As a result it is necessary to reduce the power propagating in these wavelengths in order to equilibrate the power associated with each of the separate wavelengths. (It is not practical to selectively increase the power propagating in a particular wavelength.) We are able to achieve this function by bringing the metal (tungsten) actuation plate close enough to the waveguide that light can evanescently couple from the waveguide to the metal where it can be absorbed. Since the coupling can be continuously varied the attenuation can be continuously varied. This is demonstrated in Fig. 15.

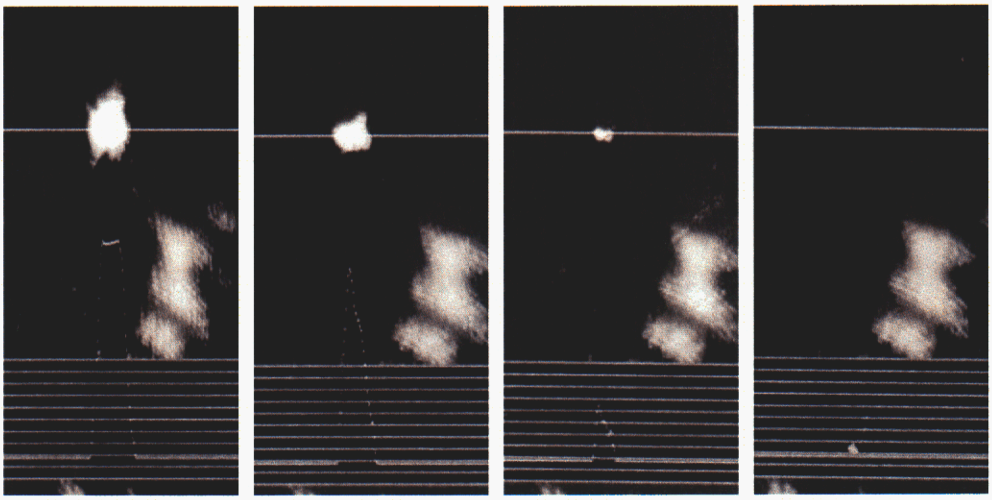


Figure 15.

Demonstration of the attenuation of the signal as the actuation plate is pulled closer to the waveguide. It is possible to continuously vary the attenuation by changing the closeness of approach by changing the actuation voltage. (The large white "blob" on the right of each image is an artifact. The beam of interest is the one near the top with the uppermost line running through it.)

Summary of Advantages and Perspectives for Future Work

The advantage of this approach is that light is guided and remains confined to the waveguides. Since the index contrast between the SiN waveguide and air is relatively large the bending radius possible using this technology is relatively tight ~50 microns. This enables a relatively high degree of integration. The MEMS actuation mechanism is very simple and adding a little more functionality would enable the use of closed loop feedback control. The voltages required are relatively low. Coupling is always a problem when going from a beam propagating in air to a beam propagating in a waveguide. We believe that we could have also applied the CMP taper approach we developed for the Si work to this SiN work.

Mechanically the main problem encountered involved pulling the actuation plate too close to the waveguides. This could be addressed by adding a simple W via between the actuation plate and the moving photonic element. The actuation voltage is relatively high, however we believe that this could be readily addressed by weakening the springs or by reducing the high tensile state internal stress associated with our CVD deposited W.

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