Comparison of robust coupling techniques for planar waveguide immunosensors

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ABSTRACT

We have analyzed and fabricated two different coupling schemes to meet the requirements for a convenient means of coupling into a planar waveguide immunosensor that is relatively insensitive to beam alignment. These are the "launch" coupler and the grating coupler. Each possesses advantages and disadvantages, depending mainly on the thickness (mode number) of the waveguide to be illuminated. For example, the launch coupler is best suited to a thick (highly multimode) waveguide and is less efficient for a thin (few mode) guide. Our experimental results verify predictions of a ray theory developed to give coupling efficiency for a variety of coupling parameters.

1. INTRODUCTION

Fluorescent based immunosensors have attracted interest in recent years due to their potential for convenience and increased sensitivity in detecting antibodies or antigens. Many of these sensors use a solid surface for attachment of the detecting protein. This solid support can also serve the purpose of introducing the excitation light into the sensor. In our immunosensor design, we use a transparent solid substrate as a planar waveguide to carry light to the sensing region. The guided excitation light is trapped by total internal reflection inside the waveguide, but its evanescent tail penetrates a few hundred nanometers away from the surface and excites fluorescently labeled antigens bound to the antibodies immobilized on the surface. This evanescent penetration gives sensitivity to bound antigens without exciting fluorescence in the bulk above the surface. Thus a homogeneous assay that does not require a wash step may be possible by this approach.

In order for such a waveguide immunosensor to be practical for commercial applications, there is the need for an efficient and convenient means of coupling in the exciting light (and/or coupling out the fluorescence) to the waveguide. This is especially important if the sensor is designed to be disposable and is to be used in a high-volume application. The coupling means must be inexpensively fabricated and must be relatively insensitive to the exact alignment of the sensor waveguide to the incoming beam. Four different methods of coupling light to the waveguide can be considered, as outlined in Table I. Prism coupling--a popular technique for integrated optical waveguide coupling--is highly efficient and is mode selective, but requires placement of a prism on top of the waveguide with a carefully adjusted gap between the prism and the waveguide.[1] This makes the prism coupling technique unsuitable for fast, alignment tolerant coupling to a disposable waveguide sensor. End coupling is simple and efficient, but the input beam from the source needs to be directed into the end of waveguide, requiring an alignment accuracy at least as small as the thickness of the guide. For thin waveguides this may be a difficult requirement, especially if the waveguides are replaceable.

We have investigated the last two methods shown in Table I: the launch coupler and the grating coupler. These approaches are described next, along with results of tests on fabricated samples.

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Table I. Comparison of four methods for coupling into a planar waveguide immunosensor.

TECHNIQUES FOR COUPLING

	Advantages	Disadvantages
Prism Coupling	High efficiency; Mode selective	Complex; difficult to align
End Coupling	High efficiency for thick waveguides	Difficult to align for thin waveguides
*Launch Coupler	Tolerant of alignment	Long, thin taper required for thin waveguides
*Grating Coupler	Tolerant of alignment; mode selective	Lower efficiency

2. THE LAUNCH COUPLER

The launch coupler is basically a fixed waveguide permanently aligned with respect to the source beam to which a removable sensor waveguide is placed in contact.[2] The input beam may be coupled from the source to this launch waveguide by any means: end coupling, grating coupling, or even prism coupling; we use end coupling. The sensor waveguide is then placed on top of the launch coupler and light is coupled into the sensor guide by simple propagation. Coupling gel (or more permanent coupling polymer) can be used to increase the index match between the two guides. This scheme allows for great latitude in the placement of the sensor waveguide with respect to the coupler. Vertical alignment is achieved automatically by the mating surfaces, and longitudinal positioning of the sensor is not critical (assuming an overlap distance of at least a few waveguide thicknesses).

Figure 1 shows two versions of the launch coupler with a sensor waveguide in place. The first version, shown in Fig. 1(a), uses a non-tapered launch guide. Ray theory predicts that the percentage of light initially in the launch guide that is coupled into the sensor is dependent on the ratio of the thicknesses of the two guides in the following manner:

$$\% \text{ Coupling} = t_s / (t_s + t_l) \qquad (1)$$

where t_s is the thickness of the sensor waveguide and t_l is the thickness of the launch waveguide. Thus, when the two guides have the same thickness, the coupling efficiency is 50%. However, when

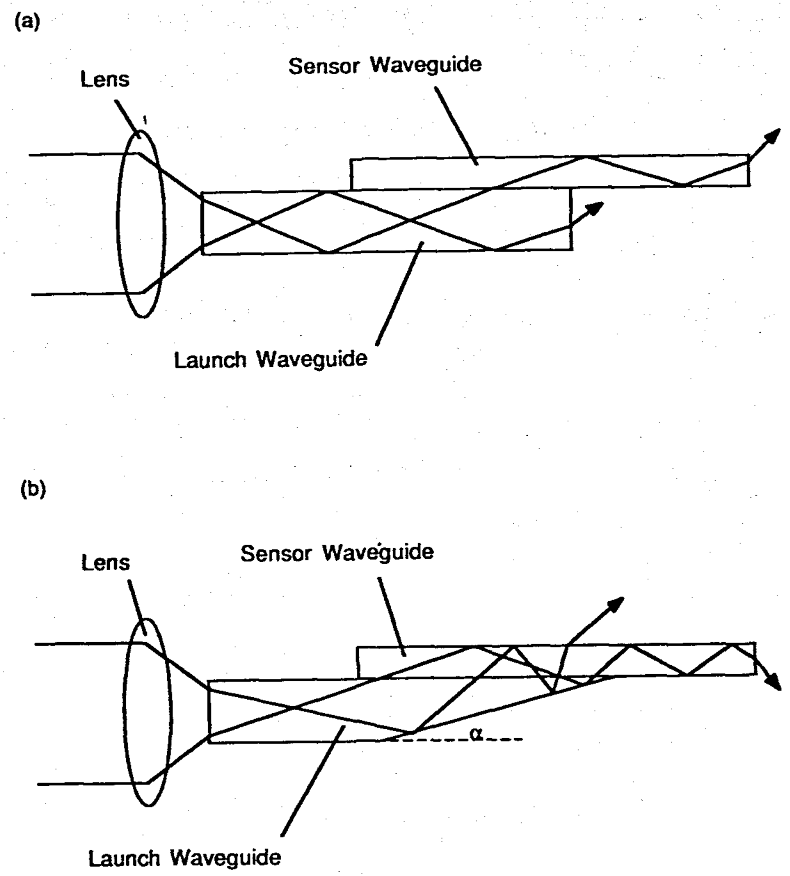

Fig. 1. The launch coupler with sensor waveguide placed on top. Two versions are shown: (a) non-tapered, and (b) tapered.

the sensor waveguide is much thinner than the launch guide, the coupling efficiency drops considerably. We have fabricated and tested a non-tapered launch coupler, and have found experimentally that Eq. (1) accurately predicts its behavior.

For thin sensor waveguides, the tapered version of the coupler--shown in Fig. 1(b)--gives higher efficiency. The design is based upon the concept of transforming narrow-angle/broad-area illumination in the launch waveguide (as initially coupled in from a laser source) into broad-angle/narrow-area light in the sensor waveguide. A ray tracing analysis taking into account multiple reflections and total internal reflection effects shows that for small taper angles, the coupling efficiency can be quite large. For example, Fig. 2 plots the theoretical coupling efficiency for a launch waveguide thickness of 1.2 mm and taper angle of 3°. It can be seen that the efficiency is near 100% for sensor thicknesses greater than 150 μm.

We fabricated a tapered launch coupler with the dimensions given above, and measured the coupling efficiency for a variety of sensor waveguide thicknesses. These data points are also plotted on Fig. 2, and a comparison with the theory shows good agreement.

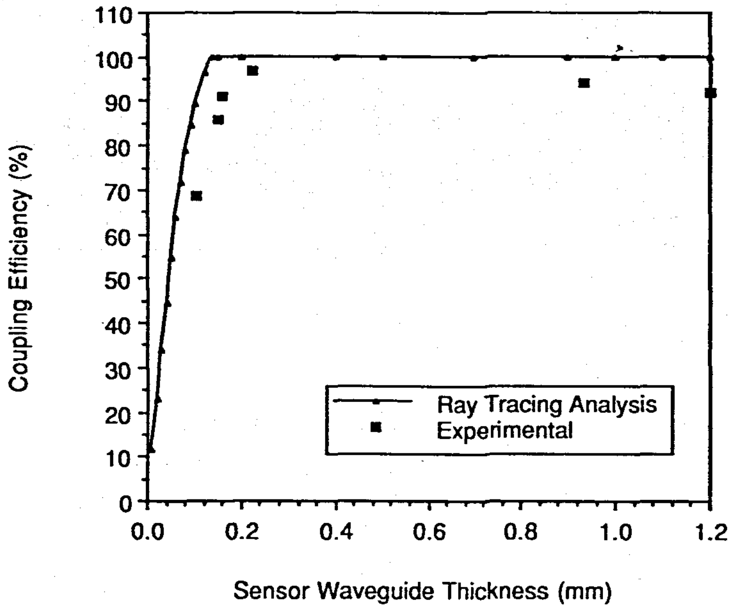

Fig. 2. Coupling efficiency of a 1.2 mm thick, 3° tapered launch coupler for varying thicknesses of the sensor waveguide. Theoretical curves from a ray tracing analysis are shown along with experimentally determined values.

3. GRATING COUPLER

Another coupling method which has the promise of tolerance in alignment is the grating coupler.[3] In our approach, we form the grating on top of the waveguide by using UV curable epoxy and an embossing technique, as outlined in Fig. 3. First we place a small drop of epoxy on the waveguide, then press a piece of a master diffraction grating which has been coated with a release agent onto the epoxy; the epoxy viscosity is low enough to fill the grooves of the master grating. Then, with the master in place, we expose the epoxy for approximately 1 minute to UV light for curing. When the master is removed, a replica grating remains on the waveguide as a coupler.

We found that the nature of the release agent is critical to good performance.[4] If no agent is used, the replica grating fractures into small patches when separated from the master, sticking partially to the master and partially to the waveguide. An attempt to use silicon oil as a release agent failed, due to the fact that the oil filled the grooves in the master preventing the epoxy from taking the shape of the master grooves. We were most successful with a release agent formed by first coating the master grating with a thin 200 Å layer of evaporated silver followed by a 4000 Å layer of evaporated aluminum. The layers were thin enough that an atomic force microscope (AFM) image of the master grating after deposition of the layers showed negligible fouling of the grooves. The silver does not adhere tightly to the master grating, so it releases when the cured epoxy replica is parted from the master, leaving a siver/aluminum layer on the outer surface of the replica.

This silver/aluminum layer actually provides an optical benefit as well--it reflects more light into the diffracted orders and thence into the waveguide when illuminated from below. Figure 4 shows the experimentally measured efficiency of coupling into a multimode glass cover slip waveguide (thickness = 220 μm) for two versions of the grating coupler (1200 lines/mm): without the aluminized reflecting coating, and with the aluminized coating. The efficiency is shown as a function of angle of the input laser beam. It can be seen in Fig. 4 that the efficiency is greater for the aluminized coupler by about twice, reaching 15-20% for the appropriate coupling angles.

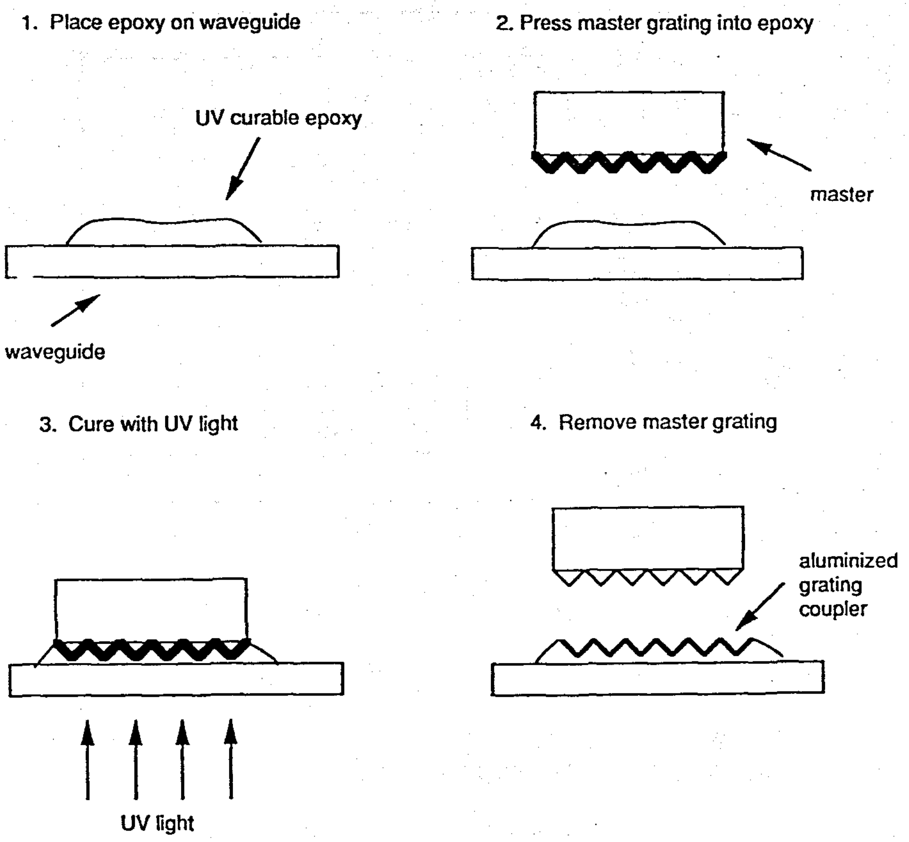

Fig. 3. Steps for fabricating the UV-curable epoxy grating coupler.

The grating coupler showed moderate tolerance to alignment. As Fig. 4 shows, there is a several degree tolerance in coupling angle. However, we found that the efficiency is somewhat sensitive to the lateral beam position on the grating for a focused input beam. The beam position had to be within approximately 1-2 mm of the end of the grating (toward the waveguiding region) to achieve the highest efficiency. If the beam was too far away from the grating end, light coupled into the guide would be coupled back out by the grating before reaching the guide, reducing the amount coupled.

We also fabricated grating couplers on thinner, fewer-mode guides, including a four-mode ion exchange waveguide in glass. In this case, the coupling efficiency was not as high, only reaching 3.5% for the $m=3$ mode and 2.0% for the $m=0$ mode. The lower efficiency was probably due to imperfections in the fabricated replica which caused angular spreading of the diffracted beams, which then did not meet the narrow angular requirements for coupling to the single modes.

4. CONCLUSIONS

Both the launch coupler design and the grating coupler showed tolerance to misalignment of the input beam (especially the launch coupler), making them candidates for use with removable and disposable sensors. The non-tapered launch coupler worked well for thick sensor waveguides (thicknesses greater than about 1 mm) and was simple in design, but its coupling efficiency dropped for thinner guides. The tapered launch coupler gave better efficiency for these thinner sensor waveguides, but fabricating the tapered end was more difficult and made the coupler end more fragile.

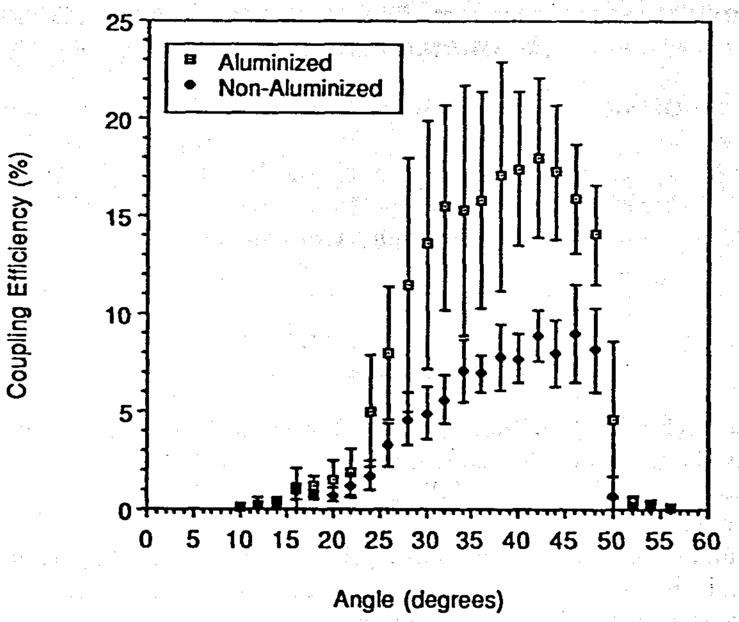

Fig. 4. Coupling efficiency of a 1200 line/mm grating coupler into a multimode (220 μm thick) waveguide as a function of incident beam angle. Values are shown with and without the reflective aluminum coating.

The grating coupler was relatively easy to fabricate once the proper release agent was determined and the molding steps worked out. The coupling efficiency of the grating coupler was not as high as the launch coupler, probably due to imperfections in the replication process. The grating coupler is mode selective however, and would be a better choice than the launch coupler for a thin-film, few-mode guide.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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