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Coupling Between Optical Fiber and Hollow Waveguides

A Thesis submitted in partial fulfillment for the requirements of the degree of Master of Science in Electrical Engineering

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STATEMENT

This Thesis is submitted to Ain Shams University in partial fulfillment of the degree of Master of Science in Electrical Engineering.

The work included in this thesis was carried out by the author in the department of electronics and communication engineering, Faculty of Engineering, Ain Shams University.

No Part of this thesis has been submitted for a degree of a qualification at any other university or institute.

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Kareem Madkour

Coupling Between Optical Fiber and Hollow Waveguides

By
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Abstract

The problem of coupling between optical fiber and hollow waveguide is studied. The hollow waveguide modal solutions are derived using two methods: leaky mode analysis and the novel "quasi-leaky-mode" analysis method. The former is traditional approximate method for such leaky structures, where the latter is a novel technique that stems from grouping the radiation modes in packets and each packet represents one of the quasi-modes. The technique is exercised on the case of hollow dielectric waveguides, both the field profile and the propagation losses are calculated using this new technique and validated versus both the leaky mode analysis and measurements.

A novel method for fabrication of hollow waveguides on silicon using simple silicon micromachining techniques is described; and the optimized process parameters are reached; we demonstrated the robustness of the process by fabricating of hollow waveguides and measuring their optical performance. Measurement came in good agreement with the calculated parameters giving confidence in both the theory of quasi-leaky modes and the fabrication process. The low losses measured are encouraging to use the hollow waveguide in various applications.

Thesis summary presented by:

Kareem Madkour Bakr Madkour

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Summary

Hollow dielectric waveguides have been introduced since the ٦٠'s of the last century, yet they received attention in the last ١٠ years more than the attention they received in the last half century. This is because of the rise of the field Optical MEMS, which enabled various functional photonic devices including optical switches, variable attenuators, tunable filters and movable mirrors. Silicon hollow waveguides have the advantage of being compatible with the MEMS micromachining techniques; that in turn shares a lot of steps with the traditional IC technology. In addition, the hollow core enables a lot of tunable and movable structures that cannot be realized with traditional waveguides.

One problem of hollow dielectric waveguides is the fact that they are not real waveguides (anti –guides) – this problem is naturally inherit from the name of hollow waveguides: being hollow means that the core has a lower refractive index hence light is not guided in the core by total internal reflection (TIR) like the traditional waveguides – but on the contrary light is leaked from the core to the surrounding clad. Hence another name for this family of waveguides is used: the "leaky waveguides". The power leakage from the waveguide made hollow waveguides not the best solution for long distance transmission, yet for small propagation distance and with the proper design of the waveguide dimensions the propagation loss can be minimized. Increasing the waveguide dimensions minimized the leakage loss, yet in turn made the waveguides incompatible with the single mode fibers (SMF). The objective of this thesis is the calculation of the coupling losses and the search for the spot size that would best match the fundamental mode of the waveguide.

In this thesis, we have calculated the field profile of the modes of the square dielectric waveguide. First, we used the leaky mode analysis method to calculate the modes of the

structure. The leaky mode analysis method gave unreal solution where the field grows away from the guide; nevertheless the solution is accurate near the guide. We calculated the spot size that would best couple to the fundamental leaky mode; and both the coupling loss and the propagation loss.

Next we used the radiation modes formulation, on the contrary to the leaky modes; radiation modes are rigorous and provide real solutions but radiation modes are continuum spectrum; so we developed a novel technique to treat a packet of radiation modes as one “quasi-leaky-mode”. We used the quasi-leaky-mode method to calculate the field profile of the hollow waveguide; and hence the spot size that would best couple to the first quasi-leaky-mode and also calculated the coupling and the propagation loss. These calculations came in good agreement with the results obtained from leaky mode analysis method.

In the remaining of the thesis, we developed the process for the fabrication of the hollow waveguide using basic silicon micromachining steps: etching and bonding. The fabrication was conducted in the clean room facility of Group ESIEE in east Paris, France. And we optimized the process for best control over the waveguide dimension and profile. Then the waveguides were characterized, we used lensed fibers to convert the spot to match the large dimensions of the guide. We measured the guide propagation loss and the coupling losses from the lensed fiber to the hollow waveguide and the result came in good agreement to the calculation using both the leaky mode analysis and the quasi-leaky-mode analysis.

In the chapter ١ we will review some applications of hollow waveguide and the traditional techniques of spot size conversion for waveguide-fiber coupling. Chapters ٢ and ٣ aim to find the mode profile of the hollow waveguide. Chapter ٢ uses the more traditional method finding the leaky modes of the hollow waveguide structure while chapter ٣ starts from the rigorous radiation mode analysis. In both chapters coupling losses is calculated between the calculated mode and the fiber mode.

Chapter ٤ studies the steps used for the actual fabrication of the hollow waveguide and the optimized process parameters. Chapter ٥ presents the measurement results of the waveguides fabricated in chapter ٤. Then we conclude the thesis with short conclusion and suggested future work.

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CHAPTER ١
INTRODUCTION

١.١ Introduction

Photonic light circuits (PLC) form an integral part of many optical communication, sensor and instrumentation devices. Silicon Optical benches (SiOBs) are one example of an assembly technology for such photonic circuits. As the name suggests, SiOBs are optical benches formed on silicon substrates, with grooves and slots etched in the silicon material using micro-fabrication process, to hold the various optical components.

In such photonic circuits the optical components are connected together by waveguides that are monolithically fabricated to ensure perfect alignment between the various components.

When an optical MEMS component exists in the bench, PLCs has the disadvantage of unwanted reflections from the end of each waveguide. This usually requires refractive index matching of the waveguides to the optical components, or the use of a gel or antireflection coating. To solve this problem, hollow core (silicon clad) waveguides provides an appealing alternative to traditional waveguides. The hollow waveguide is advantageous over traditional waveguides over many aspects. First, it removes the requirement to provide antireflection coating to prevent the unwanted reflection. Second the fabrication of the hollow waveguide is compatible with the traditional silicon micro-machining process that is widely used in CMOS and Micro-elctro-mechanical systems

(MEMS). Further advantages of linking the components with hollow optical waveguides are the increased optical power the circuit can handle typically a problem when handling infra-red waves (IR) and the temperature insensitivity of the waveguide that is challenging with silica-based waveguides. However, when these circuits are connected to an optical fiber, which is the typical case in optical communication systems, these hollow guides should be compatible with the optical fiber modes to maximize the power coupling between them. Such coupling problem is the focus of this thesis.

١.٢ Thesis Outline

This thesis focuses on the calculation of coupling coefficient between optical fiber and hollow waveguide. In the remaining of this chapter we will review some applications of hollow waveguide and the traditional techniques of spot size conversion for waveguide-fiber coupling. Chapters ٢ and ٣ aim to find the mode profile of the hollow waveguide. Chapter ٢ uses the more traditional method finding the leaky modes of the hollow waveguide structure while chapter ٣ starts from the rigorous radiation mode analysis. In both chapters coupling losses is calculated between the calculated mode and the fiber mode.

Chapter ٤ studies the steps used for the actual fabrication of the hollow waveguide and the optimized process parameters. Chapter ٥ presents the measurement results of the fabricated waveguides designed in chapter ٤. Then we conclude the thesis with short conclusion and suggestions for future work.

١.٣ Hollow waveguide Applications

١.٣.١ Optical Cross Connect Switch using Hollow waveguide

One of the main motivations for the hollow waveguide is its use as the guiding medium between the mirrors for the NxN optical cross connect switch [١]. In such application, the cross connection is achieved by inserting mirrors with ٤٥^{o} in the optical path to switch the light beam in the required direction. This could be achieved by the use of the flip chip technique between two chips: one chip contains the mirrors and the other contains the hollow waveguides. The first chip contains a matrix of movable vertical mirrors shown in figure ١.١. [٢],[٣]. The mirrors are actuated vertically using electromagnetic actuation. The chip is fabricated using a clever combination of deep reactive ion etching (DRIE) and KOH etching. This enables to obtain a good, smooth enough, optical surfaces. Figure ١.١ shows an SEM (Scanning Electron Microscope) picture of such a chip for the case of a ٤x٤ switch. The second chip contains the hollow waveguides is shown in figure ١.٢. These hollow guides are fabricated by creating vertical grooves in a silicon wafer using DRIE and then the top of the guides are closed using wafer bonding with another Si wafer. Fiber grooves are also etched in the Si to allow for the fiber insertion in the wafer with minimum alignment.

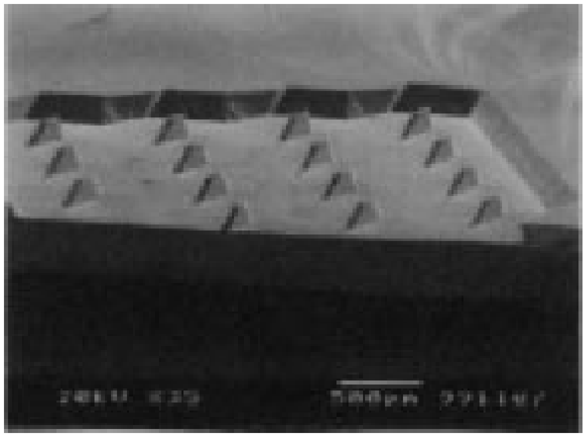

Fig. ١.١. An SEM picture of the first chip of the switch showing the matrix of ٤x٤ vertical mirrors.[٢]

Figure ١.٢, shows a picture of a ٤x٤ hollow waveguide chip before the bonding to the switch chip. A matrix of ٤x٤ switches could be observed. Across the matrix, there are ١٦ openings to allow for the moving mirrors to be inserted vertically for switching.

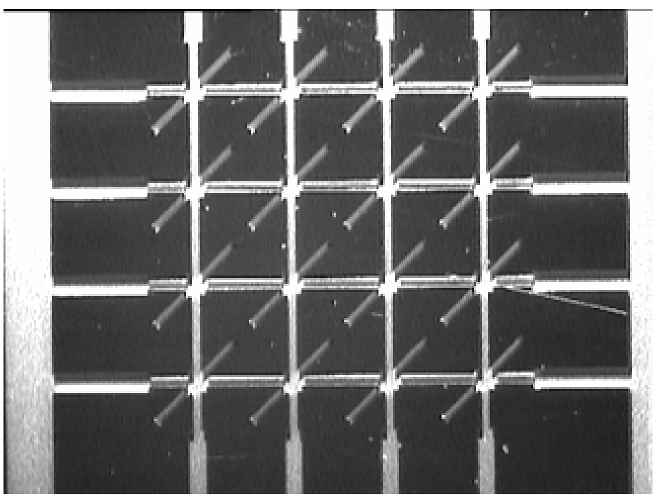

Fig. ١.٢. Waveguide Matrix with the mirror openings for the case of a ٤x٤ cross-connect.

In Figure ١.٣ we compared the losses resulting from using the Hollow waveguide to free space and conventional waveguides approaches [١]. The simulation is