Design of an Arrayed Waveguide Grating for Photonic Integrated Circuits

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Abstract

Arrayed waveguide gratings are useful structures for the implementation of wavelength division multiplexing; however, in their current form, they are too large to be made cheaply or to use as an integrated component. This paper discusses the work of the MIT Microphotonics Center, explains the operation of an arrayed waveguide grating, and discusses plans for a Master of Engineering thesis project to design a much smaller version of this device.

I. MIT Microphotonics Center

The MIT Microphotonics Center was founded in 1993 as a spin-off of the Materials Processing Center. It is an organization composed of faculty, research staff, and students from many different academic departments, including the Department of Materials Science and Engineering, the Department of Chemistry, the Department of Electrical Engineering and Computer Science, the Department of Physics, the Department of Chemical Engineering, and the Sloan School of Management. In addition to representing different academic areas, the staff of the Center also possess a broad range of experience, ranging from theory to design to fabrication. The Center also has a strong relationship with industry.

The branch of physics known as photonics deals with the use of light as a medium for transmitting information. Today it is far less popular than the field of electronics, which uses electric currents and voltages to transmit and store information. Light is employed mainly for large-scale communication in the form of fiber optic networks, while electronics continues to be the method of choice for more integrated applications such as signal processing and computation. But silicon-based electronics face problems in the near future because of fundamental limitations in speed and bandwidth. Because of these limitations, the staff of the MIT Microphotonics Center see photonics as the eventual replacement for electronics in the 21st Century. They are working to develop photonic components with all the versatility and diversity of the current electronic toolbox. To achieve this goal, the Center has active research in three separate, but strongly intertwined, areas: resonant structures and devices, integrated functionality, and new materials and processes. The rest of this paper discusses specific research in the area of integrated functionality, the study of processes to create integrated photonic circuits similar to the familiar integrated electronic circuits.

II. Color: Wavelength Division Multiplexing

An obvious advantage to photonic components is the increase in speed provided by the use of light rays as signal carriers. In fact, lasers are already being used for optical clock distribution, the transport of the clock signal to different parts of an electronic chip. But photonics also offer a second advantage over electronics by providing larger bandwidth on a single channel. This effect can be achieved by the technique known as wavelength division multiplexing (WDM). With WDM, light beams of several different wavelengths can be sent along a channel (fiber-optic cable or waveguide) simultaneously. Each wavelength can carry a distinct signal from the others.

In order to successfully apply the concept of wavelength division multiplexing, some means must be found to multiplex different wavelengths into one channel and demultiplex them back into separate channels. Such multiplexing and demultiplexing devices could have nontrivial applications in many parts of a larger photonic system. For instance, a chip could be created to detect degraded signals and regenerate them. The first component on this chip would be the WDM demultiplexer. It would split the input signal into its component wavelengths. These individual signals would be detected by electronics, which would then drive lasers to replay the signals without degradation. Finally, the regenerated signals would be multiplexed back together with another WDM device before leaving the chip.

III. Arrayed Waveguide Grating

One possible implementation of a WDM multiplexer/demultiplexer is known as an arrayed waveguide grating (AWG), pictured in Figure 1 (attached). Strictly speaking, the AWG is only a portion of the overall device, but "AWG" will be used to refer to the entire structure in this paper. The AWG consists of several input waveguides, a multimode interference coupler (MMI), an array of curved waveguides (officially the AWG), a second MMI, and several output waveguides. Light containing multiple wavelengths comes from the input waveguides and enters the MMI. This device has reflectors on both walls and is larger in size than the input waveguides, so it sets up multiple modes of propagation. These modes then constructively interfere at the outputs of the MMI. This principle is known as "self-images" and serves to couple the input waveguides to the arrayed waveguides. The light then travels down these arrayed waveguides to the other MMI. But since the arrayed waveguides are curved, they are all different lengths. Therefore, when the wavefronts reach the second MMI, they are all out of phase with one another. When they are interfered in the second MMI, each wavelength present in the original signal is coupled into exactly one output waveguide. In this manner, the AWG functions as a wavelength demultiplexer. Interestingly, the device also works in the opposite direction as a multiplexer, with wavelength-separated inputs and wavelength-combined outputs.

The design of the AWG relies mainly on determining the geometry of the arrayed waveguides and MMI's in order to set the correct path length differences and conditions for wavelength-selecting constructive interference. A working design has already been achieved, and 10 cm by 10 cm AWG's with silica waveguides on silica substrate are commercially available.

IV. Thesis Project: Shrinking the AWG

The primary goal of this proposed thesis project is to design an AWG which is much smaller than the current models. The proposed size is 10^{-2} cm by 10^{-2} cm, one millionth of the area of the current AWG. Such a size will allow the AWG to be made more cheaply and used as a component in the photonic integrated circuits of the future. The project will be supervised by Professor Hermann Haus of the Department of Electrical Engineering and Computer Science and Dr. Kazumi Wada of the Department of Materials Science and Engineering.

Although the simplest way to create a smaller AWG would be to shrink all the dimensions of the current design by the appropriate factors, a fundamental problem exists which makes this method fail. As the bend radii of the arrayed waveguides are reduced, the portion of the radiation in the cladding of the waveguide, the "evanescent wave" or "evanescent tail," must move faster around the bend in order for the entire wave to remain coherent. However, if the required speed is greater than the speed of light in the cladding, the evanescent wave will not be able to keep up, and its power will be radiated away. This process is depicted in Figure 2. To avoid potential large losses, the technique of high index contrast (HIC) has been developed. In a HIC AWG, core and cladding materials are chosen to have very different indices of refraction. Since the speed of light in a material is inversely proportional to the index of refraction of the material, proper selection of the indices can solve the problem of radiation loss. The 10^{-2} cm by 10^{-2} cm

AWG will use silicon waveguides on a silica substrate, for a index difference of 3.5 – 1.5 = 2. This difference is enough to make 98% transmission bends of radius 1 μm.

Unfortunately, the use of different materials in the small AWG means that the parameters of the current AWG design are not scalable. Thus the arrayed waveguides and MMI's must all be redesigned to achieve the multiplexing/demultiplexing effect. In addition, many other specifications must be met. These include low insertion loss into the arrayed waveguides, low scattering loss due to the index contrast, low crosstalk, and many others which will be discovered as the project begins development.

V. Design Process

The design process will consist of two iterative steps. In the first step, the equations of electromagnetism and optics will be used to guess a solution to the problem. Then the proposed design will be tested using computer simulation software. The method used is known as the finite difference time domain (FDTD) method, meaning simply that the software models the behavior of the system under test by solving difference equations in the time domain. A sample graphical output of the results is shown in Figure 3. The problems with the design will then be determined and analyzed to discover their causes. A new solution will be developed to fix these problems, and then its performance will be simulated as well. The process will repeat until the design meets all of the specifications. The final output will be a complete design, including schematic and parameter values, for the 10^{-2} cm by 10^{-2} cm AWG. In addition, an FDTD simulation will show that the design meets the specifications. Unfortunately, meeting the specifications is not the end of the story; the proposed solution may not be able to be fabricated with current technology.

However, the problem of fixing the design for fabrication purposes will not be dealt with in this thesis; it is more concerned with a “proof of concept.”

VI. Timeline and Potential Problems

The timeline for completion of this thesis project is still in its formative stages. IAP and the spring of 2002 will be devoted to integration into the research group and background reading, in order to get a better feel for the field of photonics in general as well as the specific details of this project. The formal thesis proposal should be completed by the end of the spring term. Actual design work will occur during the summer and fall of 2002, leaving the spring of 2003 to write the final thesis document. Unfortunately, it is difficult to create a more specific schedule at this time, since the technical details of the project are not completely understood. After a period of acclimation and study, a more specific schedule can be created for insertion into the formal thesis proposal.

Since the only equipment used in this project is the simulation software, there is little risk of delay due to equipment failure. The software is completely developed and has been used to solve other problems in photonics. Problems are more likely to occur in the actual design process, due to unforeseen issues. Professor Haus and Dr. Wada admit that they do not know all of the complications which may arise. Nevertheless, they are both very experienced in photonics and committed to helping see this thesis project through to completion.

References

[1] H. Haus and K. Wada, personal communication.

[2] MIT Microphotonics Center website. http://web.mit.edu/mphotonics/www.

[3] K. Wada, slides for 6.191 presentation.

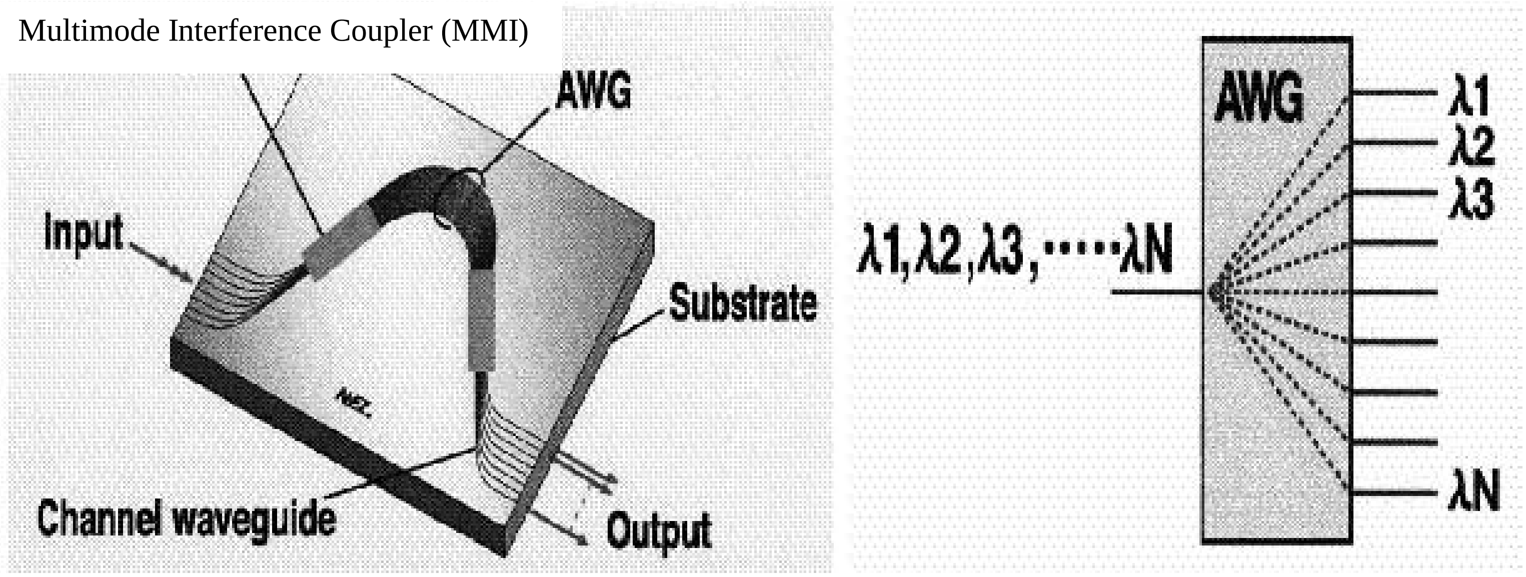

Figure 1: Arrayed waveguide grating: schematic and mux/demux block diagram
(figure from Kazumi Wada)

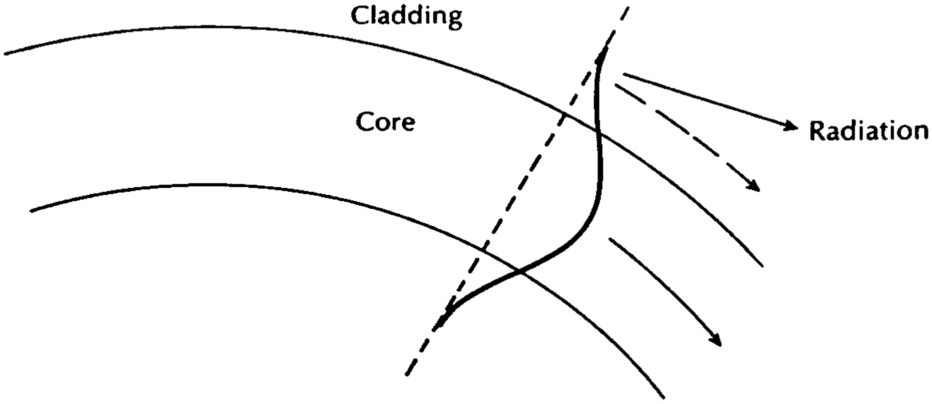

Figure 2: Electromagnetic wave traversing a bend, with radiation loss
(figure from http://serguey.sphosting.com/OPCOM/OCLec3.doc)

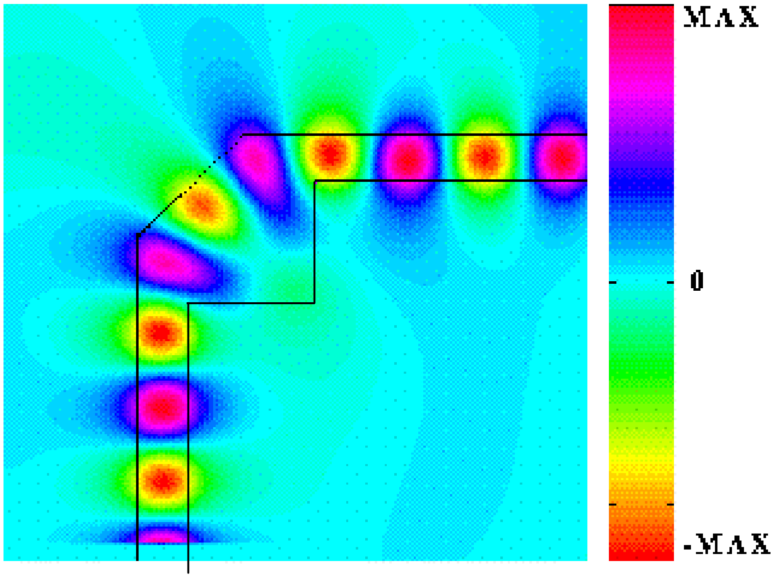

Figure 3: Sample graphical simulation of FDTD output. The colors represent electric field intensity.
(figure by Manolatou and Haus)