INTEGRATED OPTICAL FILTERS BASED ON MICRORING RESONATORS

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Cover: Microscope picture of two parallel cascaded microring resonators at resonance obtained with an infrared CCD camera. The rings have a radius of 25 μm and a width of 2 μm and are realized in silicon nitride.

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PROEFSCHRIFT

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door

Freddy Susanto Tan
geboren op 24 november 1966
te Bandung, Indonesië

Dit proefschrift is goedgekeurd door:

De promotor Prof. Dr. A. Driessen

This thesis is dedicated to
My father and the memory of my mother
My wife and children

Contents

Chapter 1

Introduction

1.1 Optical communication

The invention of the laser in 1960 [Maiman 1960] made available a coherent (i.e. monochromatic) radiation source some 10^4 – 10^5 times higher in frequency than the existing microwave generators with a frequency of about 10^{10} Hz. Since then much efforts has been spent to use the laser for communications. It was thought that a communication systems operating at optical frequencies would increase the information carrying capacity by as much as 100,000 times compared to the microwave systems existing at that time. Besides the light source also transmission lines were needed with low transmission loss to arrive eventually at optical communication systems.

In 1966, glass optical fibers had been considered as suitable and effective transmission lines but their losses were still high. In 1970, Kapron, et al. [Kapron 1970] from Corning Glass Works fabricated a silica fiber with an attenuation of 20 dB/km. At this attenuation level, the repeater spacing for optical fiber links becomes comparable to those of copper systems making the lightwave technology a practical alternative. In the next two decades, data transmission via optical fiber became more and more attractive because the attenuation of the optical fibers could be reduced below 0.2 dB/km in the 1550 nm wavelength window.

The devices that are employed in present day communication systems are a combination of electronic and optical technology. In long distance communication links, mostly optical fibers have been used and sophisticated devices have been developed with extremely high performance with respect to transmission speed, the number of wavelengths and the transmission distance.

As many users share the costs of these devices, bulk optics technology can be used with extremely good technical performance but very high cost. In short distance links, where only a few users can share the costs, mostly electronic devices are in use nevertheless their limited transmission capacity.

Nowadays, metropolitan networks are already optical and access networks are becoming more and more optical. The adaptation of solutions from long distance communications are probably not appropriate anymore for access

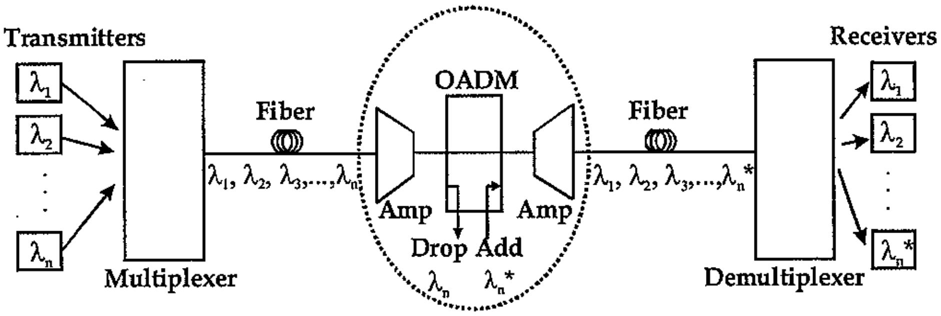

Fig. 1.1 Schematic layout of wavelength division multiplexing (WDM) systems

network where the single users are responsible for the cost by themselves. For the implementation in access network, one needs optical systems and devices, which operating at high bit rates (> Gbit/s) allow complex optical routing and data processing and are compact and low-cost without need of maintenance by trained engineers [Driessen 2003].

The rapid growth in demand for high-capacity telecommunication links and the speed limitation of electronics used in single-wavelength optical links have resulted in an extraordinary increase in the use of wavelength division multiplexing (WDM). A WDM system can multiply the transmission capacity of a single optical fiber link several times by multiplexing a large number of wavelengths and launch them into a single optical fiber.

Basic components in a point to point WDM connection are transmitters, multiplexer, optical fiber link with perhaps optical amplifiers, demultiplexers and receivers. For additional nodes in between, optical add-drop multiplexers (OADM) are necessary. This situation is schematically depicted in Fig. 1.1. At the transmitter side a WDM multiplexer connects the optical signals from *N* transmitters operating each at its own wavelength, λ_n to a single optical fiber. At the OADM, a signal of one or more specific wavelengths is dropped and new data on the same wavelengths are added. The signals arriving at the demultiplexer will be demultiplexed and each wavelength will be directed to one of the *N* receivers.

1.2 Optical filters in WDM systems

Optical filter in WDM systems can function for example as (de) multiplexer and add-drop components. There are several well-known devices that can be used as (de) multiplexer and add-drop filter such as the Arrayed Waveguide Grating (AWG) [Smit 1996], thin film filters, Bragg gratings, etc. These devices

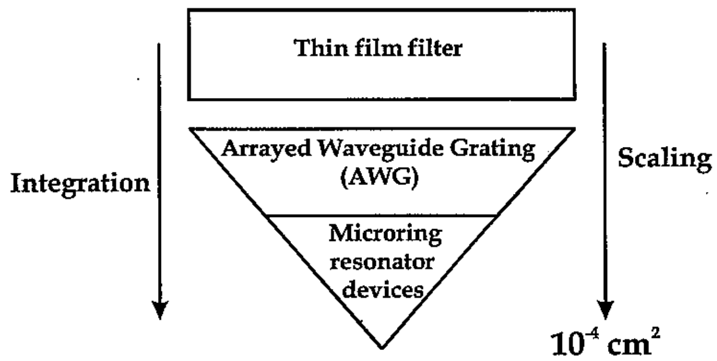

Fig. 1.2 Size reductions and integration capability of optical filter devices

are often relatively large and difficult to be integrated in compact devices with a rich functionality. Considering the success of highly integrated electronic structures fabricated in micro/nano system technology, it would be highly desirable to realize optical structures in a similar approach.

Integrated optical filters based on microring resonators can become as small as 10^{-4} cm^2 and could be promising functional elements in future large scale integrated photonics, see Fig.1.2. Compact optical filter devices based on microring resonators have been proposed since 1997 [Little 1997]. A cascaded six microring resonator device in a serial configuration (see also Sec. 2.4) has been announced on October 9, 2003 by Little Optics, Inc. [Little 2003].

There are three classes of microring resonator devices, which can be used in WDM applications. The first type is the microring resonator device with a Free Spectral Range (FSR) equal to the distance between WDM channels of about 10 - 100 GHz (0.08 nm - 0.8 nm). The second type is a filter with a FSR covering a large part of the WDM window that usually is related to the wavelength range of 1530 - 1560 nm where erbium doped fiber amplifiers (EDFA) are available. The third type is a microring based filter devices with a FSR larger than the standard WDM window, typically 50 nm – 100 nm.

The microring devices in the first category can be realized by using a moderate refractive index contrast material ($\Delta n \sim 0.05$) such as low index contrast $SiON/SiO_2$. They usually have a large radius of more than 300 μm to be able to fit the FSR to the WDM channels. In this technology, conventional optical photolithography can be applied for fabrication. Fiber to chip coupling is usually not a problem because the straight waveguides have mode profiles that usually fit to the standard optical fiber. Relatively low refractive index contrast materials also mean lower scattering loss. Filters with a FSR of 50 GHz – 100 GHz and interleaver filter for 25 GHz spaced dense wavelength division multiplexing systems based on a serial cascaded microring resonator device (see also Sec. 2.4) have been realized by using this technology [Melloni 2003]. The second type of the microring devices can be fabricated by using a large refractive index contrast material ($\Delta n \sim 0.5$) such as high refractive index SiON or Si_3N_4 in combination with SiO_2. A typical bending radius is 10 μm – 30 μm, corresponding to a FSR of about 8 nm - 20 nm.

Also this technology allows conventional optical photolithography in the realization process. Therefore, the route to low-cost technology is feasible. Fiber to chip coupling becomes critical in this technology, but simple tapering sections and the use of small core fibers result in acceptable losses of a few tenth of dB.

The microring devices belonging to the third category can only be realized by using high refractive index contrast material ($\Delta n > 2$) such as Si/SiO_2 or III-V semiconductors and allow very small bend structure down to 2 μm - 5 μm. For these devices, conventional mask-based photolithography can not be used anymore. Only advanced deep UV techniques from the semiconductor industry or direct e-beam writing can be used to obtain acceptable performance. The propagation loss of these devices is relatively high (> 7 dB/cm) and mainly dominated by scattering loss due to the high refractive index contrast in the materials [Dumon 2003]. Fiber to chip coupling loss is usually very critical and becomes a problem in this technology.

This thesis presents devices consisting of single and parallel cascaded multiple microring resonators (see also Sec. 2.4), which belong to the second category that can be used as bandpass filters, spectral slicers and (de-) multiplexers. The results that are presented in this thesis have been obtained during the work within the framework of the BTS project "ringresonatoren" and the IST project "Next-generation Active Integrated optics Subsystem (NAIS)".

1.3 BTS project ringresonatoren

The aim of the BTS project "ringresonatoren" was the realization of microring resonator devices, which can be used as an add-drop component in future DWDM telecommunication networks. There were 3 partners involved in this project founded by the Dutch Ministry of Economic Affairs: JDS Uniphase, BBV software BV, and the Integrated Optical MicroSystems (IOMS) Group (formerly Lightwave Devices Group).

In the first phase the studies have been based on a lateral coupling configuration. The material used for fabricating these devices was Low-Pressure Chemical Vapor Deposition (LPCVD) Silicon Nitride (Si_3N_4) with a refractive index of 1.98. This value was obtained by ellipsometric measurements and was extrapolated for a wavelength of 1550 nm. The devices have been designed to work for TE polarization to give sufficiently low bending loss.

Later on, the design of the microring resonator device has been based on the vertical coupling configuration. The LPCVD Si_3N_4 that has been used previously can not be used anymore for the microring core due to the requirement of polarization independence of the filter response. For the fabrication of these resonator devices, which can support only the fundamental TE and TM modes in vertical and radial directions Plasma Enhanced Chemical Vapor Deposition Silicon Oxynitride (PECVD SiON) with a refractive index of 1.65 has been chosen. It will be shown that it is difficult to obtain a polarization independent response with single microring resonator devices. By using a polarization diversity scheme, however, it is possible to make a wavelength selective polarization independent splitter, as has been proposed by Klunder et al. [Klunder 2002 (a)].

1.4 IST project Next-generation Active Integrated optics Subsystem (NAIS) project

The second project I have been involved in is the EC founded NAIS project, which has the objective to demonstrate the feasibility of a next generation compact integrated optics subsystem based on microring resonators as depicted in Fig. 1.4 [NAIS project]. In order to reach this objective, five technical Work Packages (WP's) have been considered in the project plan: materials research (WP 2), design activities (WP 3), technological realization (WP 4), characterization (WP 5) and system aspects (WP 6).

There are 12 partners involved in this EU project such as TUHH Technology GMBH, Nonlinear Optics Laboratory Institute of Quantum Electronics (ETH), Rainbow Photonics AG, Produits Chimiques Auxiliaires et de Synthese (PCAS), and Ecole Normale Superieure de Chemie de Montpllier (ENSCM), which are mainly dealing with materials to investigate the properties of new passive as well as organic electro-optic materials in WP 2. The Applied Analysis and Mathematical Physics (AAMP) Group of the University of

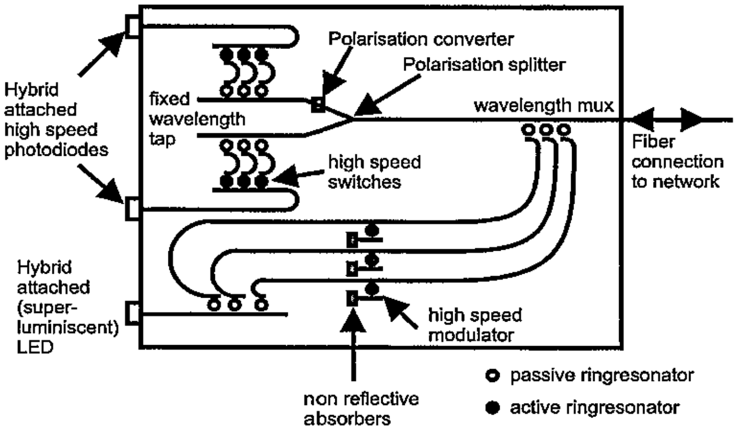

Fig. 1.4 Schematic layout of the transceiver on a single chip for an access network considered in the NAIS project

Twente, Concept to Volume (C2V) and the Institute of Radio Engineering and Electronics (IREE) are developing the simulation tools for designing active microresonators and complex integrated optics subsystems consisting of a large number of functional elements in WP 3. The Ecole Normale Superieure de Cachan (ENSC) is working on the fabrication and characterization of an active microring resonator in WP 4 and WP 5 and Universita degli Studi di Roma "La Sapienza" Dipartimento di Energitica is dealing with characterization of materials and devices in WP 5. Nortel Networks deals with the embedding of the subsystem in a network and the demands from the end-users in WP 6. Our own group, the Integrated Optical MicroSystems (IOMS) group is the coordinator and is involved in all of the WPs.

Within the NAIS project, the devices have been realized in the vertical coupling configuration. Single microring resonator devices made of LPCVD Si_3N_4 have been realized and demonstrated. Their drop response show narrow passbands, relatively low ON-OFF ratio (rejection ratio) and narrow stopbands due to the Lorentzian shape of the filter response obtained from the drop port. In order to improve the filter performance, parallel cascaded two- and three-ring resonator devices have been designed and realized in LPCVD Si_3N_4 technology. The wavelength response of these devices has shown a promising functionality as a bandpass filter as well as spectral slicer device.

1.5 Outline of the thesis

In the first phase of the present work, another Ph.D student, Dr. D.J.W Klunder was also dealing with microring resonator devices. In his work, devices with a lateral coupling configuration have been used [Klunder 2002 (b)]. The device information and basic theory already provided in that thesis is not repeated in this thesis.

This thesis deals with the design, fabrication and characterization of passive microring resonators devices. Chapter 1 gives an introduction to the development in optical communications. In addition, the projects where I had been involved are briefly presented. Chapter 2 introduces general concepts and relevant basic theory of optical microresonators and can be used as reference for the following chapters. Chapter 3 presents the design strategy for the realization of demonstrator devices. Chapter 4 presents the result of single microring resonator devices based on the lateral coupling configuration using LPCVD Si_3N_4 for the microring resonator core. A through response with a finesse of more than 100 has been demonstrated. Results on vertically coupled single microring resonators with a SiON (BTS) or Si_3N_4 (NAIS) core are discussed in Chapter 5. Chapter 6 presents the results of higher order filters. Parallel cascaded two- and three- microring resonator devices with equal coupling coefficient have been realized and demonstrated.

Chapter 7 discusses the feasibility of parallel cascaded microring resonators as compact spectral slicers with increased spectral efficiency. Chapter 8 gives a summary of this thesis and recommendations for future work.