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ABSTRACT

Recent progress in phased array-type (PHASAR) based integrated optical WDM devices like multiplexers, demultiplexers, filters and their use in integrated optical circuitsis reviewed. Design rules and their impact on technology in various material systems will be discussed. Key parameters like number of channels, channel spacing, insertion loss and polarisation (in-) dependence are addressed.

Introduction

Recently, wavelength division multiplexing (WDM) has become one of the most promising technologies for increasing network- and transmission capacity in optical communication systems. In addition, its flexibility for routing and switching has been demonstrated. Key components for this technology are multiplexers to combine a number of wavelengths with independent data streams onto the same fibre and demultiplexers to perform the opposite function. Hybrid mux/demux devices based on a grating and a set of input/output fibres have been developed and are commercially available with good performance. Size, price and mechanical stability requirements have stimulated research on integrated optical solutions. Indeed, good progress has been achieved over the last three years in design and fabrication of integrated optical mux/demux devices with improving performance.

The first solution has been to include an etched vertical grating in a slab waveguide with an input and a set of output waveguides - later also integrated with photodetectors [Soole91,93, Cremer91,92]. Parallel to this, several groups have used the concept first published by M.K. Smit [Smit88] of using a set of curved waveguides (PHASAR) with dispersion properties very similar to those of a prism and better performance (ie loss, crosstalk, and fabrication tolerances) than the integrated grating- based demultiplexer. A dramatic increase in the number of publications on integrated PHASAR based devices[*] indicates that this concept yields high performance mux/demux components leading to commercial opportunities.

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[*] *Several names are used at present for the same curved waveguide concept: PHASAR (TUDelft, Philips), Phased Array (Siemens), Arrayed Waveguide Grating - AWG - (NTT, AT&T, OKI, Hitachi).*

This paper reviews recent developments in integrated optical (de-) multiplexers and filters based on the phased array principle and focuses on passive devices and the integration with photodetectors.

Operation Principle

Figure 1 shows a schematic representation consisting of two slab waveguide star couplers connected by a focusing and dispersive waveguide array. This array is designed such that for the central wavelength the optical path length difference between adjacent array arms equals an integer multiple of the central wavelength of the array. The field distribution at the input aperture will therefore be reproduced at the output aperture and - for this wavelength - be focused in the centre of the image plane. If the input wavelength is detuned from this central wavelength, the wavefront at the output aperture is tilted due to the linear phase transfer of the array as a result of the linear variation of the channel length in the array. Output waveguides are located at the proper positions in the image plane for separation of the desired wavelength channels. The wavelength dependent shift of the focal plane is given by: $d\Theta/d\lambda_g \approx -m/d$ where $d\Theta$ is the wavefront tilt angle, λ_g is $\lambda_o/n_{g,eff}$, and $d\lambda_g = (d\lambda/n_{eff}).(1-(\lambda dn_{eff})/(n_{eff}d\lambda))$, m is the array order, d the period of array waveguides. For III-V materials, the material dispersion cannot be neglected since $(\lambda dn_{eff})/(n_{eff}d\lambda) = 0.1$.

Several array-geometries have been applied. [Vellekoop91] used a set of curved waveguides with varying radii enclosed by two straight waveguides [also Amersfoort93]. [Takahashi90] and later publications employed a fixed radius of curvature and path length differences are provided in the straight sections. This approach has a large number of junctions introducing mode conversion and coupling losses if short bends are employed. It is advantageous for low contrast waveguides (SiO_2 etc.) since this structure is free of chromatic aberration and conversion losses and is very simple from a design point of view.

The sensitivity of the optical path length of the array waveguides to fabrication tolerances and high yield from a wafer requires small devices which are only possible when low loss waveguide bends with a small radius of curvature are applied. This ismainly determined by the lateral optical contrast of the waveguide set by the material used. Radii of several mm's to cm's can be used in SiO_2 and polymer waveguides whereas radii <500 µm can be used in III-V materials. One should bear in mind that a small radius of curvature requires a bend design correction since the optical path length will change due to the radius dependence of the propagation constant. Furthermore, mode conversion at the waveguide junctions between straight and bend should be avoided by proper design.

The free spectral range (FSR) of the phased array is a design parameter and is described by the angular period $\Theta_{per} = \lambda / d$ in the output aperture plane. For filter applications, the FSR should be large i.e. the waveguide period -d- in the array small and the focal length f large. On the other hand, the FSR can also be made equal to the polarisation TE-TM shift in order to obtain polarisation independent operation.

Figure 2 shows schematic transmission curves for a 3 channel phased array operating at order m indicating a number of key parameters:

a) Insertion loss or on-chip-loss
b) Uniformity loss, ie reduction in transmission of the outer channels with respect to the central channel.
c) FSR : wavelength spacing between different orders of the array
d) Bandwidth: either -1 dB or -3 dB transmission bandwidth
e) Transmission profile: phasar based mux/demux/filters have approx. a parabolic profile with low sidelobes. It is also possible to design a flattened wavelength response by employing multimoded output waveguides.

Polarisation (In-)Dependent Operation

In general, the application of mux/demux/filters in WDM networks requires polarisation independent operation, which is not trivial. Etched grating based components [Soole91, Cremer91] do not require special measures because both the slab waveguide and the grating reflector show very little birefringence. For Phased Array devices three different options have been proposed and realized: A: Birefringence compensation, B: Order Trick and C: Non-birefringent waveguides

A: Birefringence compensation

Extensive work has been carried out at NTT to reduce the residual birefringence in the SiO_2 on Si waveguides, resulting from a large compressive stress caused by the difference between thermal expansion coefficients of silica cladding glass and a Si substrate. [Takahashi92] has used an additional patterned top layer of amorphous Si. Another solution was proposed and realised by [Inoue94] introducing a polyimide halfwaveplate in the centre of the central straight waveguide part of the arrayed waveguides for TE/TM mode conversion. However an additional loss of 5 dB was found. [Suzuki94] has shown that by using a pure silica substrate in stead of Si, a negligible wavelength response dependence on polarisation of only 0.001 nm was achieved in a 16 channel mux/demux with a 0.8 nm channel spacing. [Uetsuka95] also used SiO_2 as substrate to obtain a polarisation independent 1×8 (de-) multiplexer. Hida94 realized a 14×14 polymer based demultiplexer.

B Order Trick

The order trick is based on an adjustable FSR, which matches the TE-TM shift by designing the array such that for a given wavelength $m_{TE} = (m-1)_{TM}$. This is done by choosing the order $m=\lambda/\Delta\lambda_{pol}$ where $\Delta\lambda_{pol} = \lambda_{TE} - \lambda_{TM}$. This trick has been used by [Vellekoop91] and by [Zirngibl92], [Amersfoort94] and [Spiekman94,95]. The major disadvantage of this solution is that the wavelength span of the mux/demux has to be smaller than the TE/TM shift in order to prevent interference between different diffraction orders. This limits the number of available channels. [Zirngibl92] has demonstrated 8 channels with spacing of 0.71 nm whereas [Spiekman94] published 4 channels with 1.0 nm spacing.

C Non-birefringent waveguides

When non-birefringent waveguides are used for the phased array, polarisation independent operation is obtained since no other polarisation dependent elements are present. [Verbeek94] and [Amersfoort95] have used rectangular raised strip waveguides using "quasi-InP" (InGaAsP λ_g=1.0 μm) core material on InP substrate.

The principle of monomode operation at relatively wide (3-4 µm) waveguide width is based on the cut-off condition by radiation into the substrate for all except the lowest order mode. Due to the high lateral refractive contrast is, that compact waveguide bends (≥400µm) with low loss (<1dB/cm) can be used to reduce the overall size of the multiplexer/filter. The lowest order mode has a symmetrical profile so a high coupling efficiency (>90%) with lensed fibres has been reported. Very recently, proposals for employing strained layer quantum wells in diluted waveguides by [Bissessur95] and [Vreeburg95] at ECIO'95 indicated that for these waveguide structures, polarisation independent operation is feasible with increased design flexibility.

Applications

In addition to their elementary function, (de)multiplexers are basic elements in a number of integrated devices, some of which will be shortly discussed.

WDM-receivers. Due to the relatively simple fabrication process (only one waveguide etching step) phased arrays are particularly suited for integration with other components. Phased arrays integrated with detectors exhibit considerably lower insertion loss (4-5 dB, Amersfoort93) than integrated WDM receivers based on reflection gratings. WDM receivers can be provided of a flattened response by applying multimode waveguides at the receiver side of the phased array [Steenbergen95].

Wavelength routers. Wavelength demultiplexers can be used as wavelength routers: by choosing the proper wavelength each of the N output ports can be addressed which offers an easy means for remote power-less switching. If the phased array is provided with N input channels and N output channels and the FSR is chosen equal to N times the channel spacing the N wavelengths in each input port will be distributed among all output ports in such a way that each output port carries N different wavelengths. In this way a non-blocking 16x16 wavelength switch (or router) can be contructed with a single phased array [Dragone91].

Multiwavelength lasers. Integration of N optical amplifiers in the N input waveguides of a multiplexer on a single chip with cleaved reflecting endfaces yields a multiwavelength laser. When one of the amplifiers is powered the device will start lasing at the wavelength corresponding to the multiplexer input port. When several amplifiers are powered simultaneously the device will emit a number of wavelengths simultaneously, all of which are multiplexed into the multiplexer output port. The first integrated multi wavelength-laser based on an optical phased array was demonstrated by [Zirngibl94]. An advantage of this device is that no wavelength matching between lasers and multiplexer is required as the lasing wavelengths are determined by the integrated multiplexer, which simultaneously multiplexes all inputs into a single output port. (Amplitude) Modulation speeds will be moderate due to the size of the cavity.

Add-drop filters can be constructed by using an NxN demultiplexer to separate the different wavelengths spatially, replacing one or more signals with other signals (add-drop) and looping the replaced and non-replaced signals back to the input ports in such a way that they are multiplexed into a single output port [Suzuki94]. The choice between add-drop or feed-through can be made using one 2x2 switch per wavelength channel. Using three arrayed waveguides, [Okamoto95] have integrated a 16 channel optical add/drop multiplexer.

Access terminals and wavelength channel selectors. The loop-back configuration used in add-drop filters can also be used to construct access terminals for (N-1) remote terminals and, in combination with optical amplifiers, for use as a wavelength channel selector [Tachikawa95]

Optical crossconnects. A more futuristic application may be in optical crossconnects for Multi-Wavelength networks. In such a crossconnect a local network using N different wavelengths can be transparantly connected with N-1 remote networks through a crossconnect consisting of N demultiplexers, N multiplexers and N NxN switching matrices.

Conclusions

The very recent increase in publications on successfully realized phased array based integrated optical components like multiplexers, demultiplexers and filters in different material systems indicate that the concept of curved waveguides has been established. First commercial phasar-based products have been offered. A clear distinction can be made between all-passive devices where the preferred technology is SiO_2/Si, SiO2, or polymers where the low optical contrast does not allow for ultrasmall devices and III-V materials like InP where due to the ultrashort bends, very small demux/mux can be obtained. The very strength of III-V materials is the capability to directly integrate photodetectors onto the demultiplexer chip and to integrate optical semiconductor amplifiers with a multiplexer to obtain a multiwavelength source. Small size and high performance are critical issues for III-V's where expensive small size substrates require a high yield of devices. Thet state-of-the-art presented in this review paper indicates that key components for WDM technology are within reach.

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