Integrated 3x3 Interferometer

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Abstract
The interferometer based on the fiber 3x3 coupler is already a well-known device for measuring displacements and wavelength shifts. TNO is currently working on the fabrication of an integrated version of this versatile interferometer on Silicon-On-Insulator. The integrated interferometer is expected to be far more stable then the fiber version, making it less sensitive to vibrations, temperature and pressure variations. Also the size of the component is much smaller, making it ideal for a variety of new and smaller sensors. This paper describes the current progress on building such an interferometer for measuring small displacement and using it as a Fiber Bragg interrogator.

Introduction

Currently a fiber interferometer based on two fiber couplers is used at TNO for measuring the shift of a Fiber Bragg Grating (FBG) reflection peak, and for measuring small displacements [1, 2, 3]. A typical configuration is shown in Figure 1. In the upper geometry, one of the couplers has 3 inputs and outputs, and its three output signals have a mutual phase difference of 120°. One input is not used. The 120° phase difference creates a maximum sensitivity while eliminating the effects of the amplitude ratio on the phase measurements. Combining the three intensity outputs to a single expression for the Optical Path Difference (OPD) between the two interferometer arms, we find:

$$OPD = \frac{\lambda}{2\pi}\arctan\left(\sqrt{3}\,\frac{I_+ - I_-}{2I_s - I_+ - I_-}\right) \qquad (1)$$

We have two modes of operation:

1) Displacement measurement: the wavelength is fixed, the OPD changes due to a physical displacement of a reflecting surface. The displacement follows from the change in OPD, which can be calculated from Eq. 1.
2) Wavelength measurement (for example the reflection peak of an FBG). The OPD is fixed (typically several millimetres [3]), and from Eq. 1 we can calculate the wavelength.

The interferometer response is periodic with the Free Spectral Range (FSR), equal to $\lambda^2/n_g L$, with n_g the group index and L the physical path length difference. The read-out is therefore not absolute, however, the *change* in displacement or wavelength can be accurately followed because of the three intensity registrations which are shifted 120°. Note that with a 2-output interferometer the sign of change is unknown at constructive or destructive interference, and that the modulation depth (caused by loss, polarization) affects the output signals.

In fiber-optics, a 3x3 coupler is built by twisting 3 fibers in such a way that the evanescent wave of each fiber couples to the other fibers. The length of the coupler is chosen in such a way that the light is divided evenly among the fibers.

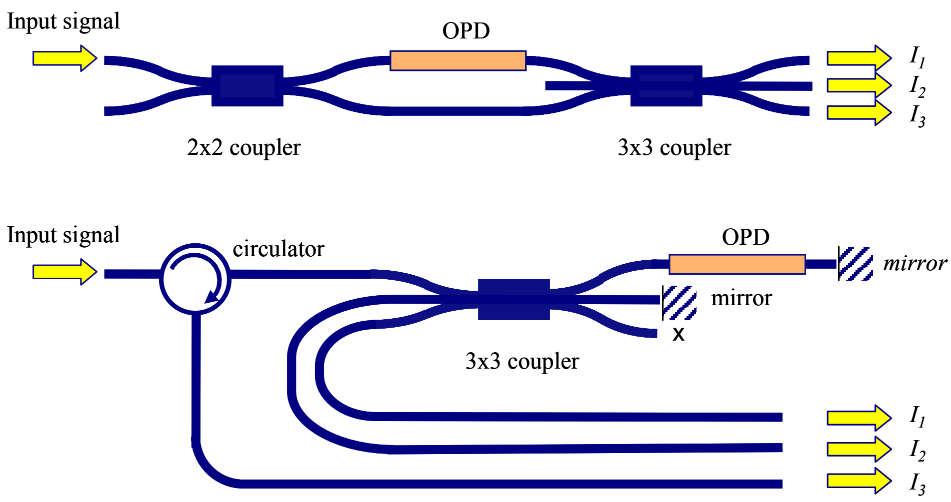

Figure 1: 3x3 fiber interferometer configurations

Integrated Optics

The fiber-optic 3x3 interferometer offers a lot of opportunities and possibilities. However, due to the relatively long lengths of fiber it is quite sensitive to temperature and mechanical vibrations. An on-chip interferometer would have a small component size and a suitable form factor for temperature control. It would enable accurate control of path length difference for wavelength measurement (FBG), and would be mechanically robust. A series of calculations and simulations confirmed the feasibility of an on-chip version. Therefore, a chip design was made with the two types of interferometers in Figure 1.

In order to obtain the 120° phase shift in the three waveguides, a way of coupling between waveguides has to be selected. Twisting the waveguides, as with fibbers, is impossible. Putting 3 waveguides very close to each other as an evanescent coupler doesn't give an equally divided signal. A solution is the use of the Multi Mode Interference Coupler or MMI. This is basically a very wide waveguide with entering and exiting waveguides attached. The MMI operation is based on the principle of self-imaging in multimode waveguides [4]. This principle states that an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction of the guide. From the mathematics behind the principle, some simple estimates for the dimensions can be made and these are put in to mode calculation software. The result (as shown in Figure 2) shows the intensity profile in a wide MMI. By choosing the appropriate length of the MMI, a 1xN or NXN coupler can be created.

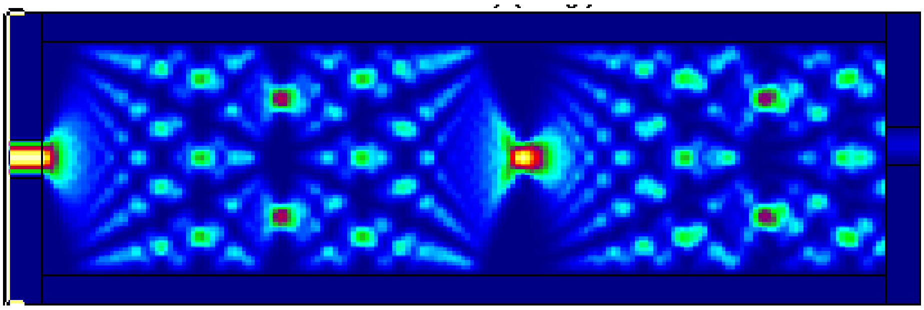

Figure 2: Intensity profile of a wide MMI. Several multi-mode images are shown at intermediate distances.

Chip Design

The designed circuit for the interferometer comes in 2 types (Figure 1). Both types have their OPD implemented on-chip, so that both interferometers are set up to measure wavelength differences rather than displacements. Figure 3 shows the mask layouts of the two different designs. Type A has an OPD that is built between two MMIs, and has 3 input waveguides on the left, and 2 output waveguides on the right. Type B is built around only a single 3x3 MMI. In order to measure the OPD, the light has to be reflected by mirrors. Using a 2x2 MMI with a looped waveguide we created these mirrors. The OPD is introduced by a length difference between the waveguides that connect the MMI to the loop mirrors. Type B has one measuring waveguide on the left and 2 on the right. The output signal in the left waveguide can be measured by means of a circulator.

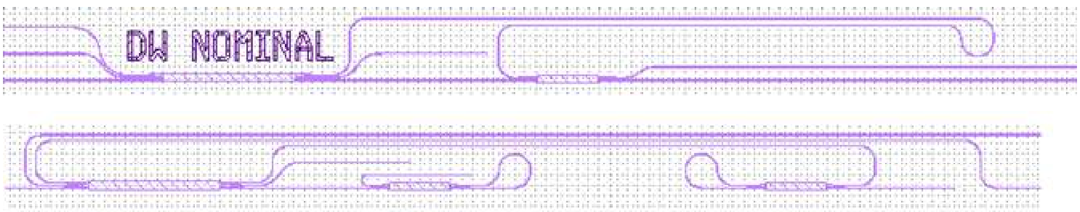

Figure 3: Design layout of the 2 types of interferometers: type A (top) and type B (bottom)

The structures shown in Figure 3 are fabricated on a Silicon-On-Insulator (SOI) chip. In order to find the optimal performances for the devices the design is placed several times on one chip. For each copy the width of the MMI is slightly altered but the waveguides all stay the same dimensions. In order to measure the devices the light has to be coupled in the chip, for which we use Vertical Grating Couplers (VGCs). The VGC is placed at the edges of the chip, and directs the horizontally propagating light to a 10° vertical direction, allowing fibers to be placed directly above the VGCs for in and out coupling.

First results

For each device, we measured the outputs sequentially, since the pitch of the outputs is 25 um, and we cannot monitor more than one output at once. The first measurements confirmed the 120° phase difference in the outputs, demonstrating the feasibility of the concept (Figure 4).

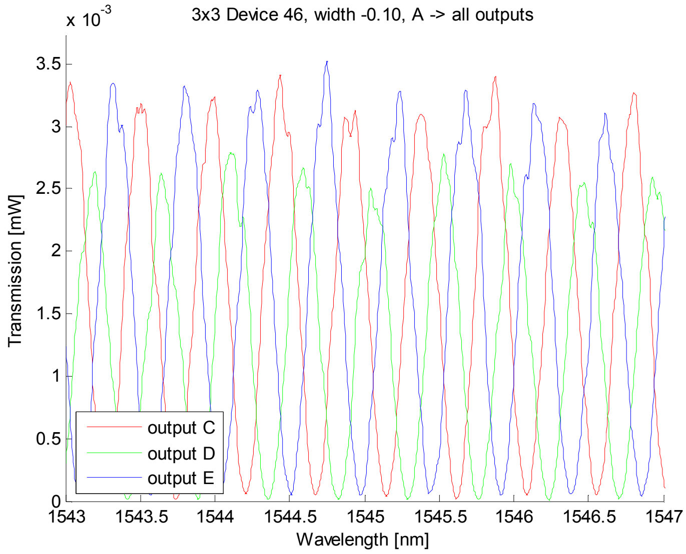

Figure 4: Responses of the 3 outputs of a type A device.

On top of the interferometer response, we note some higher frequency modulations. In fact, a Fourier transform of the response reveals several peaks (up to 8!), indicating that multiple cavities are acting together. This is still under investigation, some options we are looking into are:

- Reflections from the edge of the chip, or at the VGCs. The ripple periods disagree over 10% with the values as calculated from chip size and group index. One several chips we cut off the VGC for upcoming butt-coupling measurements.
- On-chip reflections, i.e. from the MMI, taper transitions, …
- Group indices variations. The group index used in the calculations is derived from mode calculation software. The group index depends mainly on the width of the waveguide which can vary due to fabrication.
- Measurement artefacts. Because we use cleaved fibers there is a glass-air transition before the VGC. Measurements with a lensed fiber do not show improvement, so this option is unlikely.

References

1. L.K. Cheng, R. Koops, A Wielders & W. Ubachs, *Development of a Fringe Sensor based on 3x3 Fiber Optic Coupler for Space Interferomtery*.
2. Patent application WO2004033987A1 (free access via espacenet)
3. L.K. Cheng, R. Koops, A Wielders & W. Ubachs, *Alternaticve Fringe Sensor for Darwin mission.*
4. A. Othonos, *Fiber Bragg Gratings,* September 1997
5. National Instruments, *Fundamentals of FBG Optical Sensing,* obtained on 26 October 2010 from http://zone.ni.com/devzone/cda/tut/p/id/11821 .
6. L.B. Soldano & E. C. M. Pennings, *Optical Multi-Mode Interference Devices Based on Self-Imaging: Principles and Applications.* IEEE journal of light wave technology, vol. 13, No 4, 1995

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