High speed electro optic polymer micro-ring resonator

A. Leinse, M.B.J. Diemeer and A. Driessen

Integrated Optical Micro Systems, University of Twente, P.O. Box 217, 7500AE Enschede, The Netherlands

An electro-optic polymer micro-ring resonator for high speed modulation was designed, realized and characterized. The design of layer-stack and electrodes was done such that modulation frequencies up till 1 GHz should be possible. The device consists of a ridge waveguide, defined in a negative photoresist (SU8), with a poled electro-optic polymeric (PMMA-DR1) ring-resonator vertically coupled to it. The complete layer-stack is sandwiched between electrodes to apply an electric field over the ring-resonator in order to shift its resonance wavelength. Electro optic modulation was measured up to 50 MHz limited by weak modulation depth. Optimizing the poling-process will increase the modulation efficiency thereby making modulation frequencies of 1 GHz measurable.

Introduction

In integrated optical devices for telecommunication applications the electro optic modulator is a very important component. One type of devices very suitable for using as an EO modulator is the micro-ring resonator. The modulator combines wavelength selectivity with sensitivity and is also able to modulate at high frequencies.

Device design and realization

When using micro-ring resonators as modulators there are two aspect of the design that should be taken into account. The first is to be able to generate a desired static optical behavior of the micro-ring and the second aspect of the design is its high frequency behavior. The ring designed is a vertically coupled micro-ring completely fabricated from polymers. Schematically the device is shown in figure 1.
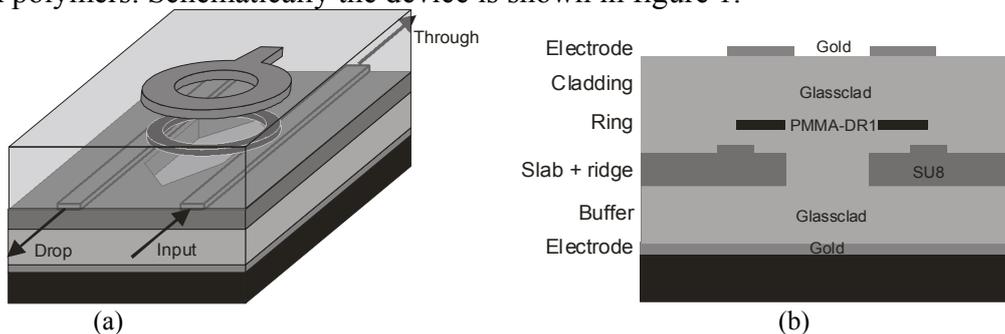

Figure 1: Schematic picture of the micro-ring resonator device (a) Schematic device (b) cross section

The device consists of two ridge waveguides with a polymer ring slightly above them. Under the buffer-layer an electrode over the entire device was deposited. On the top-layer a patterned electrode above the ring is applied. The ring-resonator is fabricated of the PMMA-DR1 polymer. This polymer consists of a disperse red-1 (DR1) sidechain connected to a methyl methacrylate (MMA) backbone (developed within the IST project NAIS by Ecole Normale Supérieure de Cachan). Definition of the ring is done

by reactive ion etching. The waveguides are defined in a negative photoresist (SU8) by a two step lithographic process. The first step is the slab layer in which the part under the ring is removed by developing it. This is done in order to prevent light from coupling from the ring to the slab-layer. The second step is a thin layer of SU8 (the ridge-layer) spincoated on top of this slab and patterned to form ridge type waveguides. For the design of the ridge and ring-dimensions the most important criterion is the fact that the waveguide and ring (ring only in vertical direction) should be single-mode. A more important issue discussed here is the high frequency behavior of the ring. When using a micro-ring as a modulator the ring needs some time to build up the optical field in the ring. One roundtrip of the light through the ring takes a time ($\tau_{Roundtrip}$),

$$\tau_{Roundtrip} = \frac{2\pi R}{v} = \frac{2\pi R n_{eff}}{c} \tag{1}$$

In which R is the radius of the ring, n_{eff} is the effective index of the optical mode in the ring, v and c the speed of light in the ring and vacuum respectively.

For a ring to build up resonance multiple roundtrips are needed. The characteristic time for the micro-ring to build up resonance is also called the cavity ring-down time τ_{cav} [1] and is given by

$$\tau_{cav} = m \cdot \tau_{Roundtrip} = m\frac{2\pi n_{eff}}{c} = \frac{F n_{eff}}{c} \tag{2}$$

In which m are the number of roundtrips and F is the finesse of the ring.

The cavity ring-down time is proportional to the quality factor (Q) of the ring and is given by.

$$\tau_{cav} = \frac{\lambda Q}{2\pi c} \tag{3}$$

The quality factor of a micro-ring is strongly determined by the fabrication process. Very high quality micro-rings give very steep through and drop responses, but have the disadvantage that the cavity ring-down time increases. It is therefore a tradeoff between sensitivity of the micro-ring and modulation bandwidth. As an example a ring with an effective index of 1.48 is considered and for different radii the $1/\tau_{cav}$ is calculated as a function of finesse. These values are given in figure 2.
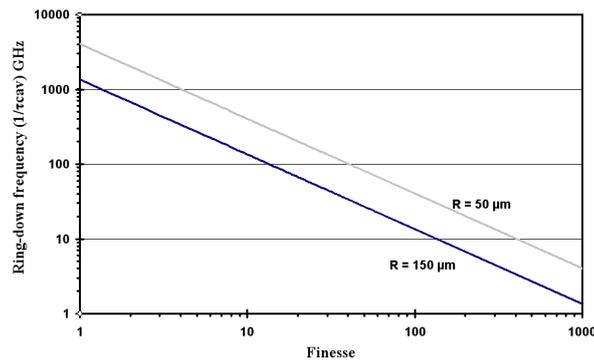

Figure 2: $1/\tau_{cav}$ value vs. finesse for two different ring radii

The values chosen in the example are realistic values for micro-rings used in the NAIS project. It can be seen from figure 2 that restrictions by the finesse are only relevant for modulation frequencies well above 1 GHz.

For high speed operation the electrode structure should have a characteristic impedance of 50 Ω and it should generate an electric field which is concentrated in the ring. The

entire device is fabricated of polymers which have a dielectric constant (ε_r) in the order of 3. To be able to connect multiple ring-resonators at the same time a wide contact lead is deposited to connect the different top-electrodes (see figure 3).
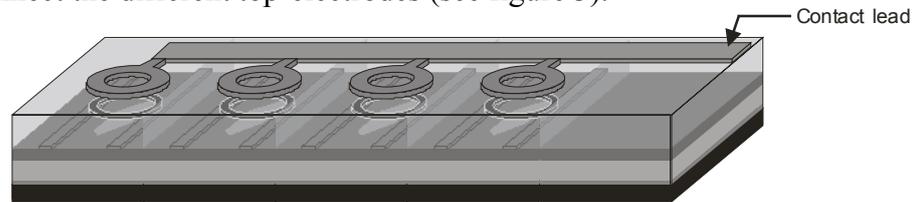

Figure 3: Contact lead to connect multiple devices

This contact lead largely determines the characteristic impedance of the electrode structure and the complete electrode structure is therefore considered as a single micro-stripline. In [2] the formulas for the impedance of a micro-stripline can be found. When calculating the characteristic impedance as a function of the width of the micro-stripline (with a thickness of 200 nm) a graph as in figure 4 can be produced.
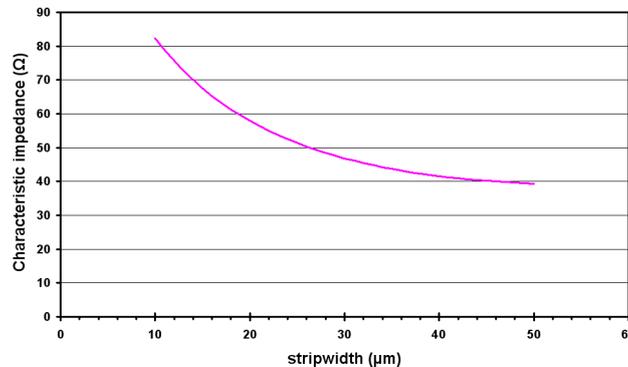

Figure 4: Characteristic impedance as a function of strip-width

From figure 4 it can be seen that an impedance of 50 Ω can be reached by making the stripline approximately 25 µm wide. Because the contact lead takes up the largest part of the total electrode area, an important frequency restriction (the RC time of the total electrode structure) can easily be calculated if the area of the contact lead is known. For the device fabricated the capacitance between top and bottom electrode is 5.5 pF. Resulting in a maximum allowable contact resistance of approximately 150 Ω to keep the RC time under 1 ns, making frequencies of 1GHz possible.

With the stripline designed it is important to know how the electrical field is divided over the entire layerstack. For high speed modulation this is only determined by the ε_r of the different layers resulting in an evenly distributed field when all ε_r values are in the same order of magnitude. In order to make the ringlayer sensitive to electrical fields it has to be poled by applying a high DC voltage over the layerstack. The distribution of this DC field is determined by the resistivities of the different layers. As long as the resistivity of the ring-layer is relatively large compared to the surrounding layers most of the field is over the ring-layer. The resistivity of the different layers can be measured by fabricating layers sandwiched between two electrodes. By measuring the resistance and knowing the surface of the electrode the resistivity can be calculated. This was done for all three materials. Table 1 gives the values of the resistivities of the different materials at both room-temperature and at the poling-temperature.

Material	25°C	135°C
Glassclad	$1.4 \cdot 10^8$ Ωm	$4.0 \cdot 10^8$ Ωm
SU8	$2.6 \cdot 10^8$ Ωm	$1.3 \cdot 10^8$ Ωm
PMMA-DR1	$4.5 \cdot 10^{15}$ Ωm	$3.3 \cdot 10^{15}$ Ωm

TABLE 1: Resistivities of the used materials

It can clearly be seen that the resistivity of the ring-layer (PMMA-DR1) is much larger than of the rest of the layers. The electrical field will therefore be largely over the ring-layer while poling it.

Characterization

Ring-resonators as described before were realized in the MESA[+] cleanroom institute and characterized at the integrated optical micro systems group. A through-port response as measured on a ring with a radius of 150 µm is given in figure 5a. Figure 5 b gives the optical signal of the through port while a 50 MHz modulation signal is applied between bottom and top-electrode. The wavelength chosen was the grey dotted line in figure 5a.

(a)　　　　　　　　(b)
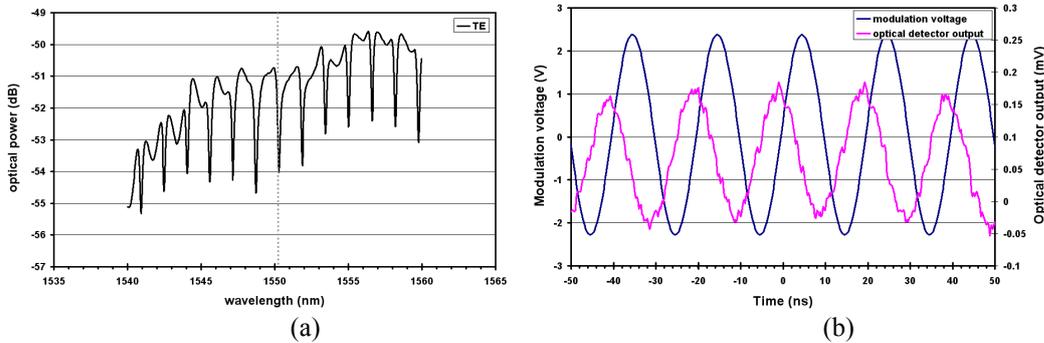
Figure 5: Through port response (a) and modulation response (b) of a micro-ring with a 150 µm radius

The maximum measurable modulation frequency was 50 MHz because the modulation depth was small and the detector needed to measure it was sensitive but not suitable for high speed operation. Optimizing the poling-process would increase the modulation depth and therefore make it measurable for high frequencies.

Conclusions

A polymer electro optic ring-resonator was designed and fabricated. The functionality of the modulator was demonstrated up till a modulation frequency of 50 MHz. Optimizing the poling-process should make it possible to reach modulation frequencies of at least 1GHz.

Acknowledgement

References

[1]　Joseph T. Verdeyen, "Laser electronics, third edition", Prentice Hall, New Jersey 1981

[2]　H.W. Johnson, M. Graham, "High speed digital design", Prentice Hall Inc., New Jersey 1993