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HAL Id: hal-00935088

https://hal.archives-ouvertes.fr/hal-00935088

Submitted on 4 Feb 2014

Characterization of electrooptic polymer applied to microwave sensing

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Abstract— In this paper we present electrooptic measurement of a crosslinked side chain PGMA/DR1 polymer. Measured values are as high as 11 pm/V at 1310 nm, we present measurement as a function of incident beam reflexion point and show dependance between the reflexion point location over the sample and the measured electrooptic coefficient. We present low frequency relative dielectric constant using a capacitance measurement method. Using this method, we found a relative permittivity of 4.46 ± 0.38 for our polymer. We present a new electrooptic microwave sensor, where we enhance the electrooptical interaction by increasing the optical path length using a Fabry-Perot cavity and we concentrate the electric field inside our device using a microstrip resonator. Expected interaction enhancement value is expected to be as high $3 \ 10^5$ compared to the simple reflexion case at low frequency.

I. INTRODUCTION

To transport information at high bit rate over great distances, fiber optic is fully adapted : low cost, low losses. But when comes time to connect each user to the backbone network using fiber to the home (FTTH) technology, cost goes incresingly higher. In fact, a large part of the network's cost comes from the infrastructure deployment to the user, more precisely the last mile.

A relevant approach is microwave communications, through Local Multipoint Distribution Service (LMDS), for data to the user transmission. However, nowadays optoelectronics transmitters have several drawbacks. They are expensive to produce, and present high electrical power consumption. In this paper we present a new device, using a low cost polymer electro-optic antenna.

We describe here the receiving part of the device : the user sends the signal to our optoelectronical transmitter. Then the device has to receive the microwave-carried information, and to convert it directly to optical one. The convertion procedure uses the second order non linear electrooptical effect, where the electrically-induced optical index variation modifies the propagating optical waves speed, resulting in a polarization change. As a first approach, lithium niobate could be used : high electrooptic coefficient, time stability, and electrooptical modulation has been demonstrated up to 40 GHz[1]. However, this material presents high dielectric constants ($\varepsilon_r \approx 43$ and 28) and index ($n \approx 2.2$), and moreover high production cost. The difference between optical index and microwave dielectric constant causes a velocity mismatch between optical and radiofrequency waves, which limits the modulator bandwidth.

Since two last decades, research has focused on new low cost electrooptic performant materials, and organic poled polymers have emerged. Those materials present a low dielectric constant ($\varepsilon_r \approx 3$ [2]) and optical index ($n \approx 1.6$), reducing the velocity mismatch and then enhancing the modulator bandwidth up to 102 GHz [3], [4]. The main drawback of polymer is stability over time and temperature : electrooptical properties tend to decrease as time goes on. Here we present a stable polymer, a PGMA backbone with a side chain DR1 chromophore. The long term stability is achieved by a epoxide cross-linkable function [5], attached to the backbone. This polymer combines the well-known PGMA/DR1 electrooptic properties with long-term stability provided by cross-linking. In the following we will present the microwave and electrooptic polymer characterization, compulsory steps for the sensor design. The last section will discuss of the sensor itself.

II. ELECTROOPTICAL CHARACTERIZATION

To measure the electrooptical coefficient r_{33}, we use the simple reflexion technique proposed by Teng and Man [6], as shown on Fig. 1. The required parameters are the modulation
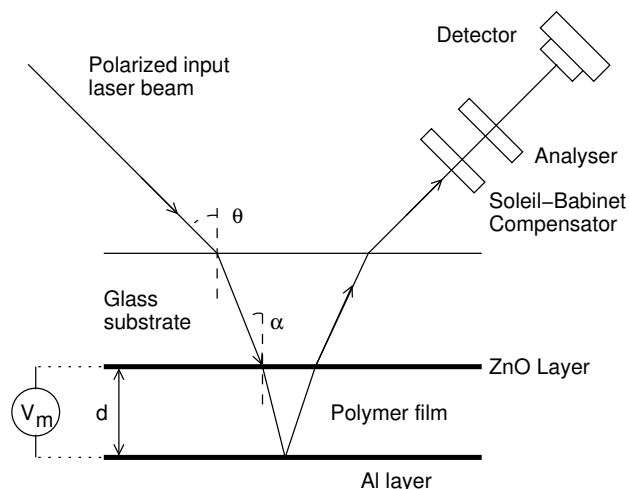

Fig. 1. Electrooptical measurement principle as proposed by Teng and Man.

voltage V_m applied across the sample, the polymer's optical index n, the intensity measured before the analyser I_{max}, the optical beam modulated intensity I_m, the incidence angle θ and the wavelength λ. From the measurement of those

parameter, the electrooptical coefficient is deduced using [7]

$$r_{33} = \frac{3\lambda}{2\pi V_m} \frac{\sqrt{n^2 - \sin^2\theta}}{n^2 \sin^2\theta} \frac{I_m}{I_{max}} \qquad (1)$$

A. Sample preparation

Samples were prepared using a glass subtrate, first coated with 1-μm-thick ZnO as bottom electrode. Then the polymer, dissolved in (1,1,2-Trichloroethane), was spun-cast on the ZnO. The samples were then poled by corona effect, by applying 5 kV over 1 cm between the pin and the ground electrode and warming the sample up to the glass transition temperature and then cross-linking temperature. Thereafter, the top aluminium electrode was evaporated as a 12 mm x 15 mm rectangular surface.

B. Measurement results

Measurements were made over 3 samples, results are presented table I. We measured r_{33} values as high as 11 pm/V for sample 2 at 1310 nm. Since measurements were made using a random location over the sample, we obtained the electrooptic coefficient as a function of the measurement location point, where the incident laser beam reflects over the electrode. Results for sample 1 are shown Fig. 2 We find out that the electrooptic coefficient varies from 4 pm/V to 6 pm/V. The cause of this variation seems to be the corona poling method, where poling effciency depends from the pin-tip placement.

Sample	Wavelength (λ)	EO coefficient (r_{33})
EO-1	1310 nm	4.02 $\pm$ 1.18 pm/V
EO-2	1310 nm	6.96 $\pm$ 1.73 pm/V
EO-3	1310 nm	2.45 $\pm$ 0.39 pm/V
EO-1	1550 nm	1.36 $\pm$ 0.33 pm/V
EO-2	1550 nm	7.97 $\pm$ 1.48 pm/V
EO-3	1550 nm	2.42 $\pm$ 0.23 pm/V

TABLE I

ELECTROOPTICAL COEFFICIENT MEASUREMENT RESULTS

III. DIELECTRIC CONSTANT MEASUREMENT

For the microwave design of the electrooptic antenna, we have to know the relative dietric constant of the polymer. The main constraint for the electric measurement is the thickness of the polymer layer, in a range from 1 to 5 μm. Thus, we used a capacitance method to measure the dielectric constant. The capacity C of a condensator is a function of the electrodes surface S, the space between electrodes, or polymer thickness, d and the dielectric constant ε_r :

$$C = \varepsilon_0 \varepsilon_r \frac{S}{d} \qquad (2)$$

Measurement of the capacity C, the surface S and the thickness d leads to the dielectric constant.

For the experiment, we used samples of 16 aluminium electrodes, 2-mm diameter, evaporated over the polymer layer. The polymer was deposited by spin coating at 4000 rpm during 30 seconds, on an aluminium layer over a glass substrate. The capacity of each condensator was measured at 1 MHz using
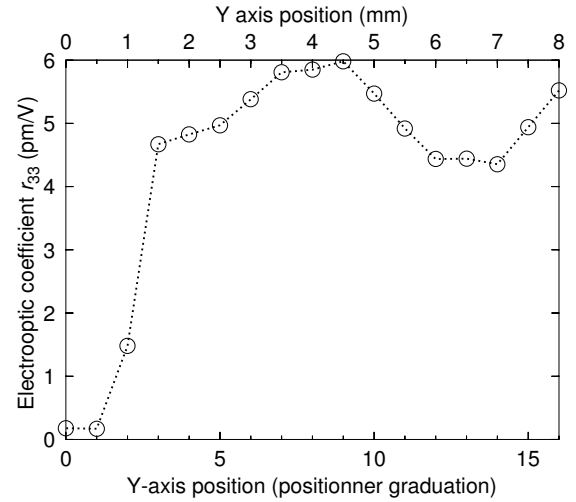

Fig. 2. Electrooptic coefficient as a function of measurement location. The beam is centered along the x direction. On the figure, the bottom electrode, optically used as a mirror layer, starts at $y = 1$ mm.

impedance/gain-phase HP4149A. Cutting samples deposited in the same conditions leaded to the thickness measurement by SEM. The precision is $\pm$ 50 nm.

There was 3 samples of 16 condensators, meaning 48 capacity measurements. Capacity measurement results are shown Tab. II. The evaluated thickness is 920 $\pm$ 50 nm. We reported table II the permittivity computed using this value. Therefore, the average permittivity is ε_r = 4.46 $\pm$ 0.38.

Sample	Mean capacity	Permittivity
ER-1	131.8 $\pm$ 1.5 pF	4.36 $\pm$ 0.30
ER-2	133.7 $\pm$ 1.7 pF	4.42 $\pm$ 0.31
ER-3	138.9 $\pm$ 1.7 pF	4.60 $\pm$ 0.32

TABLE II

PER-SAMPLE MEAN CAPACITY AND ESTIMATED PERMITTIVITY.

IV. ELECTROOPTICAL ANTENNA

Considering the simple reflection technique for electrooptic coefficient measurement, the measurement procedure can be done at microwave frequencies. Moreover, instead of electricaly exciting the device with a coaxial cable, one can avoid connexion problem using a free space incident wave. Hence we have an electrooptic antenna.

However, sensitivty can be enhanced by increasing microwave/optical interaction.

A. Optical Fabry-Pérot resonator

As a first approach, this can be done using the Fabry-Perot effet : the polymer layer may be sandwiched between two mirrors, the top aluminium electrode and a dielectric mirror as shown on Fig. 3. We experimentally measured the reflexion coefficient of aluminium and found a value of r_{al} = 0.911 at best for a 1310 nm wavelength. Using a value of r_{diel} =
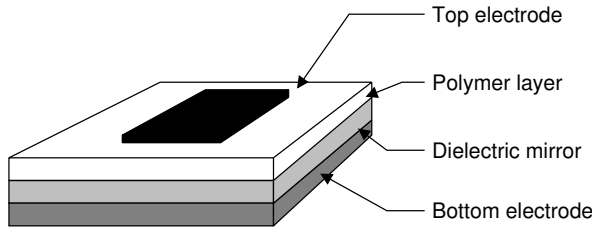
Fig. 3. Structure of the proposed electrooptic microwave sensor. Top electrode, polymer layer and dielectric mirror are considered as a Fabry-Pérot cavity, whereas top electrode, polymer layer and bottom electrode are considered as a microwave resonator.

0.9949 [8], we can compute the photon lifetime τ_p inside the Fabry-Perot cavity [9] :

$$\tau_p = \frac{1}{\alpha_r} \quad \text{where} \quad \alpha_r = \alpha_s + \frac{1}{2d} \ln \frac{1}{r_{al}^2 r_{diel}^2} \qquad (3)$$

with α_r the total optical losses and α_s the polymer optical losses, and right hand side second term the reflexion losses. This leads to the mean photon optical path length :

$$l_p = \tau_p \frac{c}{n} = \frac{1}{n\alpha_r} \qquad (4)$$

Since we expect to increase the path length up to a few tens of microns, as a first approximation we can neglect the polymer optical losses α_s. With previously mentionned values, we find l_p = 15.2 μm. Comparing this value to the single reflexion case, $l = 2d/\cos\theta$ = 2.82 μm where d = 1.2 μm and θ = 35°, the optical patch length is 5.4 times greater.

B. Resonant antenna

The rectangular aluminium top electrode is modelised at microwave frequencies as a microstrip transmission line, and the open ends as parallel admittances. The patch dimensions are L x W with a substrate heigh h and a relative permittivity ε_r. Using the equivalent slot concept, the real part of the parallel admittance represents mainly the radiation effect of the antenna. According to this model, the unloaded antenna factor of a microstrip antenna is [10] :

$$Q = \frac{\pi}{2} \frac{Y_c}{G_r} \qquad (5)$$

Where $G_r = 2(G_s + G_m)$ is the sum of the slots conductances, and Y_c the characteristic admittance of the microstrip line. Here, the susbtrate is very thin leading to a W/h ratio of 10^4. Hence, we can consider the effective permittivity and the effective line width defined by Van de Capelle equal to the relative permittivity and the line width respectively. The slot conductance is defined as a function of the normalised slot length $w = kW$, $k = \frac{2\pi}{\lambda}$:

$$G_s \approx \frac{1}{\pi\eta} \left\{ w\text{Si}(w) + \frac{\sin w}{w} + \cos w \right\} \qquad (6)$$

the mutual conductance G_m between the two slots is given by $G_m = F_g G_s$ with the auxiliary coupling function F_g (considering normalised slot width $\ll$ 1) :

$$F_g \approx J_0(l) \qquad (7)$$

where $l = kL$ is the normalised slot space and J_0 the Bessel function of the first kind. The characteristic admittance Y_c is :

$$Y_c = \frac{1}{Z_c} = \frac{\sqrt{\varepsilon_r}}{\eta_0} \frac{W}{h} \qquad (8)$$

With L = 15 mm, W = 12 mm, h = 1 micron and ε_r = 3, at resonant frequency, $G_r \approx$ 1.52 mS and Y_c = 55.1 S. The unloaded quality factor is then Q = 56 941. This quality factor provides us with the maximum order of magnitude we can expect for the field concentration inside our antenna.

Using the Fabry-Perot effect and the top electrode as a patch antenna, we can then enhance the interaction between optical and microwave signals of a factor up to 300 000.

V. CONCLUSION

In this paper we presented the electrooptical polymer synthetised at University of Nantes. The measured electrooptical values are as high as 11 pm/V, but we showed that the values are dependent of the measurement location. We presented the low frequency relative dielectric constant of this polymer of ε_r = 4.46 ± 0.38.

We then proposed a new electrooptic antenna principle, where the electrooptical interaction is enhanced by increasing the optical path length using a Fabry-Perot cavity. The electric field is concentred inside the device, using the top electrode as amicrostrip resonator. Expected interaction enhancement is as high as 3 10^5 compared to the low frequency simple reflexion technique.

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