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Thick-film piezo actuators for SOS devices

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Abstract - **We report on a new method for pathlength actuation of silica-on-silicon (SOS) integrated optics devices. Compared to the commonly employed thermal actuation by dissipation in a resistive film, the proposed method has the advantages of no dc power consumption and of a faster (down to microseconds) response. Also, we discuss the integrated fabrication of several elements by means of thick-film silk-screen printing of piezoelectric inks and appropriate conductive inks for the electrodes.**

I INTRODUCTION

Virtually all integrated-optic devices require a sort of trimming of pathlength to work properly. Examples are interferometric devices like AWG's, Mach-Zehnder modulators, but also couplers, switches, etc. The pathlength actuation is commonly achieved by a thin resistive layer evaporated over the waveguide, in which by Joule-dissipation one gets a thermo-optical control of pathlength.
Thermal actuation is rather slow (response times 0.1-1 ms) and a substantial power is demanded in CW operation, typically 300-500 mW per element, thus impeding the use of extensive thermal control on chip. In this paper we propose a piezo actuation [1] and show that it is feasible for integrated fabrication on a chip, with an improvement of both the power dissipation (zero in CW) and the speed of response (down to microseconds).
In the following we compare thermal and piezo actuation finding a substantial agreement with data measured on routinely fabricated SOS Mach-Zehnders (made by 10-mm waveguides and two 50-50 2x2 couplers). For the comparison, the interferometers were actuated on one leg either thermally or through a 7-mm length PZT-piezo cemented to the substrate (fig.1).

II ANALYSIS

An analysis of thermal and piezo actuations has been carried out in [1], and the main results are summarized below. The pathlength variation in the guide, due to thermal dissipation of a power P, can be written as:

$$\Delta(nL)= \zeta\ nL\Delta T_g = \zeta\ nL\ K_t P\eta \qquad (1)$$

where L is the actuator length, K_t (°C/W) is the thermal resistance from the layer body to the ambient, ζ =dn/ndT+dL/LdT is the thermo-optical coefficient of the guide (ζ =8.1·10^{-6} °C^{-1} in silica [2]) and η is an efficiency factor.
Expliciting the thermal resistance as [3]: K_t=[ln(4L/W)]/$\pi\kappa$L, where κ=0.014 Wcm^{-1} °C^{-1} is the thermal conductivity of silica, we get:

$$\Delta(nL)=\zeta\ n\ [\ln(4L/W)/\pi\kappa]\ P\eta \qquad (2)$$

and, by letting $\Delta(nL)=\lambda/2$ as the switching condition, we get for the drive power:

$$P_{\lambda/2} = \pi\kappa\lambda/[2n\ \zeta \cdot \ln(4L/W)\eta] \qquad (3)$$

For our experiment at λ=1500 nm, with L=4.2 mm, W=25 µm, η=0.12 (from simulations), eq.(3) gives $P_{\lambda/4}$=370 mW, a value close to the measured one (420 mW). Such a high value is primarily due to the small constant ζ of silica [eq.(3)].
About response time, the main effect is the time constant $\tau=K_t{\cdot}C_t$ of the layer, C_t being the thermal capacity of the layer. As it is [3]: $C_t=c_{sp}\pi W^2L\cdot\ln(4L/W)$, where c_{sp}=0.24 J cm^{-3} °C^{-1} is the specific heat of silica, we have found [1]:

$$\tau=(c_{sp}/\kappa)[W\cdot\ln(4L/W)]^2 \qquad (4)$$

Eq.(4) yields τ =0.45 ms, whence a risetime (10-90% points) T_r = 0.99 ms in fair agreement with the experimentally measured (T_r =0.75 ms).
Now, going to analyze the piezoelectric actuation, the pathlength variation is [1]:

$$\Delta(nL)= p_{11}\ nL\ S_1 = p_{11}\ nL\ d_{13}E_3\ \eta \qquad (5)$$

where S_1 is the strain, p_{11} is the strain-optical coefficient of the guide (=0.121 in silica), and d_{13} is the piezoelectric coefficient of the PZT ceramic (d_{13}= -420· 10^{-12} C/N); the factor η again accounts for incomplete stress coupling from piezo to waveguide. Letting $\Delta(nL)= \lambda/2$ in (5) gives the switching field as:

$$E_{\lambda/2} = (\lambda/2p_{11}d_{13}nL)/\eta \qquad (6)$$

and for L=7 mm as in our device it is $E_{\lambda/2}$=1500 V/mm, or$V_{\lambda/2}$=1500 V for the switching voltage that corresponds to η=0.44 in the experiment.
The response time is determined [4] by the time spent, at the velocity of sound v_{ac} (= 3000 m/s), to go across the sample thickness T and establish a standing

wave. Thus we have Q (quality factor of the ceramic) times the period of the resonant frequency $v_{ac}/2T$ as the minimum response time:

$$\tau = 2QT/v_{ac} \tag{7}$$

For T=1mm, Q=2, (7) gives τ=1.2 μs, near to measured data (2 μs). The product $\tau\, E_{\lambda/2}$is independent from L and one can trade-off half wave voltage and speed. In the piezo actuation, no power is dissipated in dc. On switchings, however, the energy $1/2CV^2$ (1.4mJ in our setup) is dissipated in the external circuit.

III INTEGRATED PIEZOS

The drive voltage can be substantially decreased in a practical design, e.g., by employing two piezos in push-pull arrangement to halve the voltage. Also, thinner elements or a multilayer ceramic could be used, reducing by a factor 3-5 the required voltage, down to a reasonable 100-200V.

An approach [5] easy to implement is shown in fig.2: two multilayer SMD ceramics, much alike SMD (surface-mount-device) high-ε capacitors, are used in push-pull to drive the guides. The SMD's can be mounted with pick-and-place on solder pad previously deposited on the SOS with standard electronic manufacturing assembly techniques, very common in the thick-film circuit technology.

With a multilayer piezo (n=8 layers) of L=5mm, W=1mm, T=2mm, a drive voltage of 50 V and a switching time of 2μs are anticipated. With this small W, several actuators can be placed aside for actuation in multiguide SOS.

Even better to increase the integration density is the approach of thick-film printing, going down to a few mil line resolution as required, e.g., by AWG's (fig.3). Piezoelectric inks have been reported [6] for sensor applications and they exhibit, when fired with a thermal profile similar to that of thick film electronic devices, piezoelectric constants close to the bulk values, and good long-term stability.

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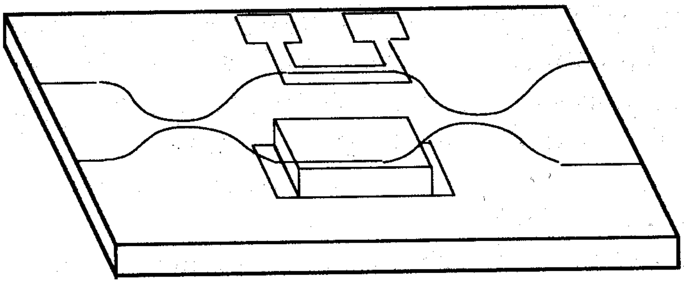

Fig.1. A SOS Mach-Zehnder interferometer with thermal and piezo actuators on legs

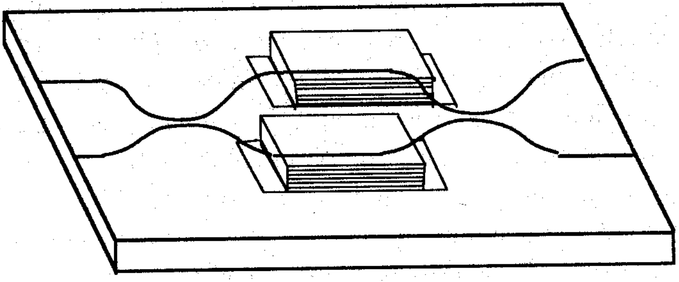

Fig.2. Actuation by means of SMD piezos

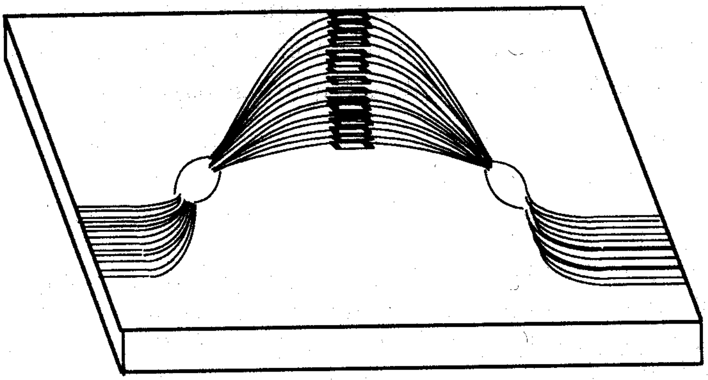

Fig.3. Actuation by means of thick-film ceramic-ink piezos