42.7 Gbit/s electro-optic modulator in silicon technology

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Abstract

◆ Goal: Low modulation voltage & high speed modulation

◆ A solution: SOH(silicon-organic hybrid) platform
  - the electro-optic effect is provided by an organic cladding with a high $\chi$-nonlinearity
  - a highly conductive electron accumulation layer which is induced by an external DC “gate” voltage
  - data encoding is demonstrated at a data rate of 42.7 Gbit/s
Backgrounds

Silicon does not possess a $\chi$-nonlinearity due to its centro-symmetric crystalline structure -> the bandwidth of silicon-based modulators is limited.

**State-of-the-art silicon modulators: plasma effect phase modulators**

- **Forward biased junctions:**
  - low voltage-length product, $V\pi L = 0.36 \text{ V mm}$
  - low modulation speed because of the dynamics of minority carriers, data rates of 10 Gbit/s

- **Reverse biased junctions:**
  - high bandwidth about 30 GHz,
  - high voltage-length product, $V\pi L = 40 \text{ V mm}$
Backgrounds

<Polymer Silicon Hybrid Systems>
- nonlinear optical polymer claddings + silicon waveguide
- nonlinear polymer is poled by applying voltage
- based on the Pockels effect
  (an electric field changes the refractive index of a poled material)

➢ Advantages
- tight optical confinement in the slot -> efficient modulation
  (n of Si: near 3.48, n of polymer: typically from 1.5 to 1.7)
- The nonlinear polymer can provide large 2\textsuperscript{nd} and 3\textsuperscript{rd} order optical nonlinearities.
- Advanced fabrication technology for silicon
Device in this work

- SOH (silicon organic hybrid) approach

- Coated with an electro-optic organic material which fills the slot
- Modulating voltage drops off across the slot, the resulting electric field changes the index of refraction in the slot.
- Slot width in the order of 100 nm, a few volts generate very strong modulating fields
- A high modulation efficiency since both the modulating and the optical fields are concentrated inside the slot
- metal-insulator-semiconductor (MIS)
- $V_{\text{gate}} \uparrow \Rightarrow$ a high-mobility electron accumulation layer
- the free-electron density $\uparrow \Rightarrow$ $R$ of Si strip $\downarrow \Rightarrow f_{RC} = \frac{1}{2\pi RC}$ $\uparrow$ (limiting frequency)
Specification of the Device

• Slot depth : 1um
  Strip thickness : 60nm
  SiO2 thickness : 2um

• organic material M1 was deposited and poled
  - nonlinear electro-optic coefficient up to $r_{33} = 70 \text{ pm/V}$
  - $n = 1.67 \pm 0.02$ at $\lambda=1550 \text{ nm}$

• 1.7 mm of phase shifting section
Device characterization

<experiment setup>

- 42.7Gbit/s electrical signal, 1550 nm laser as an optical source
- delay-interferometer converts the phase modulation into intensity modulation for detection
- Bit-error-ratios $< 3 \times 10^{-10} \Rightarrow$ usable in real data link
Phase modulation index $\eta$ vs. modulation frequency (1kHz~60GHz) (for selected electrical gate fields)

- $E_{\text{gate}} \uparrow (-0.025 \text{ V/nm} \sim 0.135 \text{ V/nm}) \rightarrow$ the silicon strips become more conductive
  $\rightarrow$ modulation index $\uparrow$
- $V_{\pi L} = 9 \text{ V mm at 1kHz} (58 \text{ V mm at 60GHz})$
- Between 2 GHz and 60 GHz, the frequency response decrease is less than 3dB
  $\Rightarrow$ data rates could be extended beyond the 42.7 Gbit/s
Modulation index vs. gate field
(for selected modulation frequencies)

- Each curve becomes flat at high gate fields.
- When $E_{\text{gate}} = -0.025 \text{ V/nm}$, n-doped strips are fully depleted of free electrons -> a minimum modulation index.
- At more negative fields, formation of a conductive hole inversion layer -> modulation increase.
Advantages

- Silicon strips can be much thinner
  -> More concentrated optical field

- No more doping is required
  -> mobility remains high, lower losses

- Thinner SiO2 -> gate field -> strip resistance ↓
Summary

• The first 42.7 Gbit/s operation of an SOH electro-optic modulator is demonstrated.

• the conductivity of the thin silicon electrodes is increased by using a electron accumulation-layer technique

• the modulation increased by a factor of five at 60 GHz while the optical loss increased by less than 1 dB.
Reference

- L. Alloatti, D.Korn et al. “42.7Gbit/s electro-optic modulator in silicon technology”