Femto-farad nanophotonic devices for fJ/bit signal conversion

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Abstract: We use a photonic-crystal platform to demonstrate opto-electronic devices and integrated functions with a femto-farad capacitance. This allows us to realize amplifier-free photo-receiver, electro-optic modulator, and O-E-O signal converter operating in a fJ/bit energy consumption.

1. Introduction

Given the important role that optical technology has played in the optical transmission of information in telecommunication and data communication, there is a demand for photonics to be employed in signal processing and computing components in close conjunction with electronic circuits [1, 2]. To this end, we need an electrical-to-optical (E-O) converter that employs an electro-optic modulator (EOM) and an optical-to-electrical (O-E) converter that employs a photodetector (PD) to greatly reduce both size and energy consumption and thus achieve densely-integrated optical interfaces with CMOS electronics.

On the other hand, we also address an optical nonlinear device (which can control the optical signal similarly to an electronic transistor) that can outperform existing electronic processors in terms of operating speed and delay. Such optical nonlinear devices have been studied, for example, by combining E-O and O-E converters and configuring an O-E-O converter [3]. However, both the size and energy consumption have been very large, since a strong light is generally needed to reveal the optical nonlinear effect.

The fundamental problem for these devices stems from the capacitance (C), which is as large as 100 femtofarads (fF) for the traditional photonic devices and is recently reduced down to fF order with Si-photonics devices (Fig. 1). We have been developing a semiconductor nanostructure called photonic crystal (PhC) with which to realize various tiny optical devices [4]. In this work, we used our nanotechnology to demonstrate E-O/O-E/O-E-O converters with extremely-small C and energy consumption that cannot be achieved with any other photonic technology. Lowering C down to 1 fF or less suggests that the charging energy required to drive CMOS logic electronics can be still used to drive the opto-electronic devices, which would enable the seamless interface between CMOS layer and photonic layer without energy-hungry signal amplification.

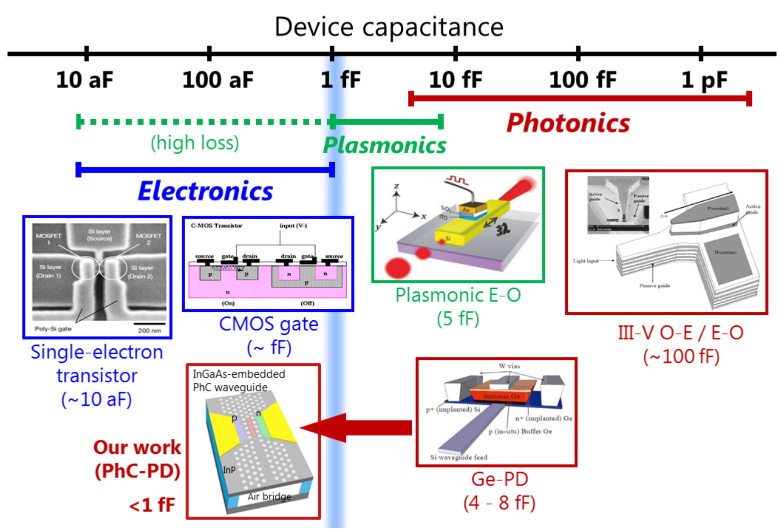

Fig. 1. Typical capacitance for various photonic/electronic devices.

2. Advantage of ultralow-*C* photodetector

In terms of O-E conversion, there are various advantages for an ultralow-C nano-PD [5], as shown in Fig. 2. Conventional PDs incorporate a transimpedance amplifier (TIA) and some stages of voltage amplifiers to generate the required voltage to drive the electronic circuit. However, such devices have problems in the purpose of dense integration, including large energy consumption on the order of 100 fJ/bit or more, as well as having a large delay and footprint. One approach is to connect the PD with high load resistor (R_{load}) for a simple receiver configuration that performs light-to-voltage conversion. In this case, there is a trade-off that the light-to-voltage conversion efficiency is proportional to R_{load}, but the operation bandwidth is inversely proportional to the RC time limit, so this approach is generally inappropriate for conventional PDs. The extreme reduction of C would solve this problem, and consequently, an amplifier-free receiver with an energy consumption of only fJ/bit level can be expected.

With a conventional receiver the thermal noise primarily limits the receivable optical energy at up to several magnitudes larger than the shot noise limit. Since there is no amplifier and the thermal noise is remarkably suppressed for our resistor-loaded PD, better noise characteristics should be expected. We experimentally measured the noise equivalent power (NEP) of less than 1 pW/√Hz for our PD terminated with 59-kΩ resistor. Theoretically, such low noise enables an optical reception with a sub-100 aJ for an SNR of more than 144 (corresponding to a bit error rate of 10^{-9}).

The amplifier-free receiver should also have advantage in delay and footprint. A small signal delay or latency is important for a short-reach optical link, because the advantage of photonic wiring would be hidden if a receiver circuitry had a larger delay than the time-of-flight delay of light. For a resistor-loaded PD without any delay overhead due to amplifiers, the delay should be simply determined by the single RC time limit; for example $R_{load}C$ = 10 ps is expected for R_{load} = 10 kΩ and C = 1 fF. For the conventional receiver, a transimpedance of the 10 kΩ level may require multiple post amplifiers or greater gain per amplifier stage, and therefore have a larger delay.

In the practical integration with electronic circuits, a resistor-loaded PD would be directly connected to a load capacitor such as a CMOS FET gate through a via connection. A small footprint of less than 100 μm^2 can be expected for such a configuration, while a conventional photoreceiver occupies much larger space for the integrated amplifier circuit. Since the metal vias will affect the load capacitance, the close connection using an InP-on-Si heterogeneous integration technique should be important [6].

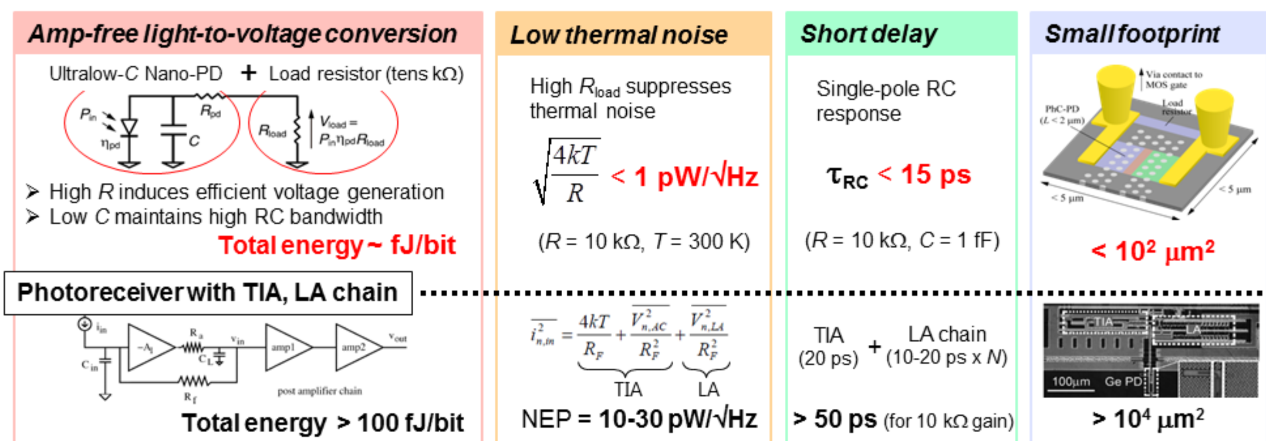

Fig. 2. Several advantages for ultralow-capacitance nano-PD.

3. Energy-saving O-E-O converter based on PD-EOM integration

As well as an ultrasmall PD, we also realized a tiny EOM by using a PhC nanocavity with a length of only 1.3 μm. Thanks to the embedded InGaAsP in the nanocavity, the Franz-Keldysh effect occurs when a voltage signal is applied to the p-i-n junction, and consequently changes the resonant transmission of light. Light was successfully modulated at a bit rate of 40 Gbit/s, and the record-low operating energy of only 42 aJ/bit was achieved, which is dominated by the charging energy used for the theoretical capacitance (0.6 fF) of the EOM with a driving voltage of 0.5 V [7].

By closely integrating the nano-EOM and the nano-PD, we realized a compact O-E-O converter (Fig. 3). In the operation, an optical signal is converted to photo-current by the nano-PD, and subsequently converted to the photo-voltage by the load resistor. This voltage drives the nano-EOM, and thereby the signal is transferred to another light with a different wavelength. Depending on the incorporated load resistance (4–24 kΩ) and consequent RC limit, we observed the O-E-O signal conversion at a bit rate of 10 – 20 Gbit/s. Conventionally, integrated electrical amplifiers are required when converting an optical signal into a signal with a voltage high enough to drive an EOM. However, our device can perform this conversion by using just a high load resistance without any amplifiers, and therefore greatly suppresses the energy consumption. The minimum optical energy injected into the PD is only 1.6 fJ/bit, which is more than two orders of magnitude lower than previously reported O-E-O converters. Our analysis of the operating speed and RC time constant showed that the device capacitance was only 2 fF. This is the first experimental proof of opto-electronic integration with fF capacitance.

With the optical conversion operation, the output signal power can be more than twice than that of the input optical signal. This reveals the signal gain achieved in the optical nonlinear operation, which is proof of "optical transistor" action. In fact, it has been difficult to reduce the size and energy of previous O-E-O devices. Thanks to the signal gain, our optical transistor will be able to be cascade-connected and thus realize densely-integrated signal processing in a photonic layer.

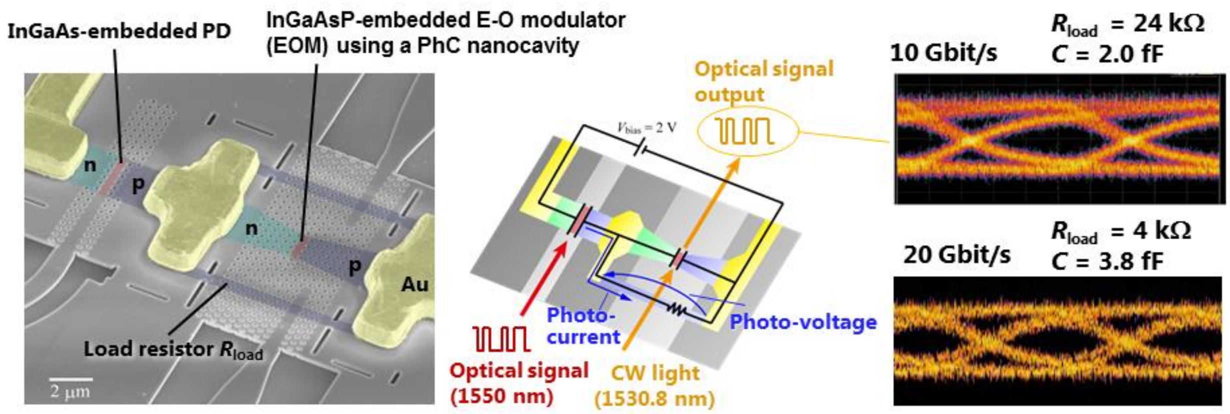

Fig. 3. Nonlinear O-E-O converter by the combination of low-capacitance PD and EOM.

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