doped by boron (1.3 × $10^{15}$ $cm^{-3}$), with a 2-µm-thick native oxide layer underneath. The DI resonator design was patterned by electron-beam lithography and then etched by deep reactive-ion etching to completely remove the silicon layer to form 450 × 220 nm channel waveguides. Finally, a 1-µm-thick oxide layer was deposited on top by plasma-enhanced chemical vapour deposition. The chip was coated by a standard resist and diced to form a 1 × 1 $cm^2$ square chip. Tapered waveguides at the facet of the resonator were also fabricated so that external fibres could be easily connected. The DC was used to split input light and form two beams with different amplitudes and phases while a conventional Y-coupler was employed to equally split the incoming light. Various transmission responses, such as triangular, square, sinusoidal, notch (2 × FSR), peaks (2 × FSR) and spikes (tangent-like), were demonstrated in the active DI resonator by properly selecting different coupling coefficients and input coefficients (Fig. 2). The obtained response shapes are in fair agreement with theoretical simulations. These obtained response shapes are of practical relevance for transmitters and receivers for various radio-frequency analog and digital applications. The unique characteristics of the DI resonator operating in two FSR states for the same resonator length could be used to achieve wider operation bandwidth with low power consumption in advanced transmission techniques.

Interestingly, a parameter-insensitive response (PIR20) device exhibits twice as large tolerance range for the extinction ratio of 20 dB compared with that of a conventional MZI and is more tolerant compared with a conventional ring resonator, which is favourable for mass production and reliable operation owing to lower sensitivity to fabrication defects, temperature and the electro-optic effect. Experimentally, demonstration of at least 20 dB attenuation with extended bandwidth and low operation voltage (2 V) makes the PIR20 DI resonator a potential candidate for large-scale integration.

The engineered transmission response shapes with twice as large FSR compared with a conventional ring resonator of the same size and improved tolerance obtained in the DI resonator device should be useful for large-scale integration and practical applications. Some challenges do however need to be overcome. First, the performance of such DI resonators needs to be further addressed; although designed response shapes have been obtained experimentally, the efficiency of the transmitted light is unclear, which is an important practical factor. Second, for integrated optics, more optical elements are required and it is not yet known how to arrange DI resonators within a chip to avoid interaction with adjacent elements. The gain, loss and energy- or power-dependent nonlinearity have to be considered when designing a silicon-based DI resonator for various practical applications. Nevertheless, with further efforts, the silicon-based single ring DI resonator should be a potential and useful candidate for large-scale integration of photonics. ❐

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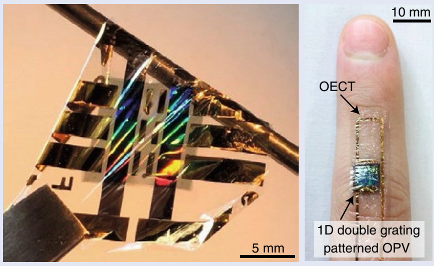
SOLAR CELLS

# Self-powered sensors

The realization of thin, flexible self-powered electronics and optoelectronics has taken a step forward with the demonstration of a solar-powered cardiac sensor that wraps around a finger. The approach offers a route to the development of stand-alone, self-powered, wearable biomedical sensors.

To create the device, Sungjun Park and co-workers from Japan and South Korea fabricated an ultra-thin, flexible organic photovoltaic (OPV) cell (pictured, left) as a power source and integrated it with organic electrochemical transistors (OECTs) on an elastomer substrate (*Nature* **561**, 516–521; 2018). The OPV was just 3 µm thick and consisted of a PBDTT-OFT:$PC_{71}BM$ organic heterojunction sandwiched between a ZnO nanoparticle layer that served as an electron-transport layer and an upper electrode of Ag/$MoO_x$. The OPV operated with a power conversion efficiency of ~10% and weighed just 36.6 µg and was capable of generating 11.46 W $g^{-1}$ of electrical power.



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A key innovation for the success was the patterning of both the photoactive organic polymer layer and the ZnO layer with a 1D grating to improve the efficiency of the device. The 760-nm pitch grating pattern was taken from the surface of a blank DVD-R.

After fabrication, the devices were delaminated from a glass substrate and transferred to a thin layer of parylene. The OPVs were then integrated with OECTs to demonstrate self-powered, on-finger cardiac sensors (pictured, right) based on gate-bias-induced changes in output current when illuminated with light from an LED. The peak intensity and standard deviation of the recorded cardiac signal were 0.47 µA and 23.5 nA, respectively. Comparisons to the use of a commercial battery as power source, showed the benefit of no external power line noise, and no ground-loops due to the short interconnections. ❐

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