optical effects are usually only observed over a fairly narrow range of frequencies. The range cannot be adjusted or tuned and a new sample has to be fabricated if effects at other frequencies are desired. Essentially all of the interesting effects achieved with metamaterials so far, such as negative refraction[5] and cloaking[6] at microwave frequencies, and negative group and phase velocity in the infrared region[7], have been limited to a fixed and relatively narrow spectral bandwidth.

Hou-Tong Chen and co-workers have overcome this limitation using a clever metamaterial design, which allows the resonant response to be tuned by a near-infrared light beam. They have constructed a planar metamaterial consisting of a two-dimensional array of split rings on a silicon-on-insulator substrate. They selectively remove the silicon by etching, leaving just a thin silicon layer in two strips within each split-ring resonator (see Fig. 1). These two strips form the two plates of a capacitor. The mechanism of the tuning is that when a near-infrared laser pulse illuminates the entire array, it modifies the conductivity of the exposed silicon through photoexcitation of charge carriers. This changes the effective capacitance of all of the split rings simultaneously, and consequently shifts the resonant frequency of the material.

For initial tests, the results are impressive. The authors show that the resonance (initially at 1.06 THz) broadens with little shift when the photoexcitation is weak, but that a pronounced redshift of the resonance of about 20% can be obtained under a stronger photoexcitation. Interestingly, at the highest excitation level, the charge density in the silicon is high enough to mimic metallic behaviour, which lowers the damping. As a result, the resonance narrows again, but it remains centred at the lower frequency. This behaviour is reproduced by a detailed finite-element simulation. Chen *et al.* have also performed simulations on two other types of array element, where photoexcitation of the silicon is used to modify the inductance of the ring rather than the capacitance. Using this approach, they show that they can shift the resonant response to a higher frequency rather than to a lower frequency, on photoexcitation.

Despite the significance of these results, several important challenges and open questions remain to be addressed. Various parameters need to be investigated, such as the degree of tuning, the depth of modulation, and optimization of the resonance line width. If this device were to be used as a dynamic modulator, its maximum modulation rate is unknown. This rate could possibly be influenced, to some degree, by ion implantation in the active silicon region, but this idea is yet to be investigated. Also, the ability to tune the resonance using an electrical approach rather than an optical approach would be extremely useful[2]. And, of course, the idea of scaling these effects to infrared or optical frequencies is appealing. This work opens up a rich new area of study in the field of active terahertz devices.

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QUANTUM OPTICS

Beyond single-photon counting

The ability to distinguish how many photons comprise a particular state of light leads to significant benefits in practical quantum information processing and quantum cryptography. Superconducting nanostructures provide an effective solution at telecom wavelengths.

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Optical quantum information processing is at the frontier of modern physics and optics. It is a topic that relies heavily on manipulating single-photon states: exciting experimental applications, such as quantum cryptography, entanglement swapping and quantum-state teleportation, would be impossible without single-photon-counting detectors[1]. The most critical parameters that must be considered when designing such detectors are high speed, low noise and high quantum efficiency; a poor-quality single-photon detector has a deleterious effect on the fidelity of the quantum-state manipulation. On page 302 of this issue[2], Aleksander Divochiy and an international team of researchers working on the European collaborative project SINPHONIA has demonstrated a detector capable of counting the number of photons in an optical state at telecom wavelengths — achieving so-called photon-number resolution (PNR). The integrated, parallel, multisection device combines their expertise in creating superconducting single-photon detectors (SSPDs) based on NbN nanowires with modern technological advances in nanoscale lithography.

The problem of detecting single photons and evaluating their statistical behaviour was brought to the forefront of physics about 50 years ago by the famous Hanbury Brown and Twiss experiment[3]. This demonstration of the non-classical properties of light gave rise to the field of quantum optics. However, it would have been impossible without single-photon-counting detectors, which can convert the energy of a single incident quantum of light into a macroscopically detectable pulse of voltage or current. Photomultiplier tubes (PMT) are one example of a single-photon-counting detector. Initially developed for the purpose of counting high-energy quanta in nuclear physics, they have found their way into optical applications.

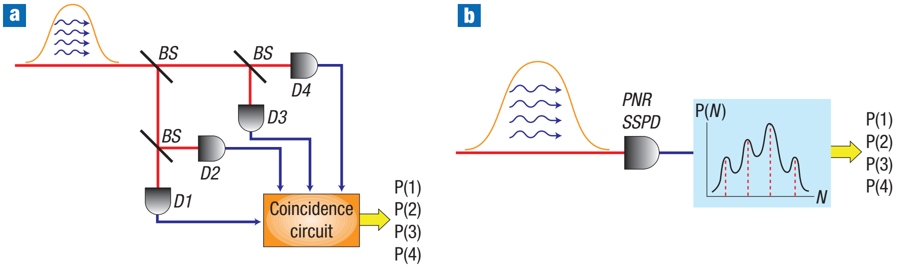

Figure 1 Implementations of a photon-number-counting detector. **a**, Correlation measurements with several single-photon detectors (D1–D4) and optical beam splitters (BS) enable the calculation of the fraction of events with more than one photon[7], P(1)–P(4). **b**, An SSPD provides an integrated, high-speed, low-noise approach to photon-number (*N*) counting[2].

More recently, with the development of semiconductor technology, a new generation of photon-counting devices such as avalanche photodiodes (APD) has also appeared.

The development of practical quantum communications and quantum cryptography has created a need for photon-counting detectors that operate reliably within the telecommunication window of the optical spectrum[4]. The semiconductor InGaAs is commonly used for near-infrared detectors; however, the practical implementation of InGaAs APDs has been problematic because of a high level of spontaneous noise that triggers false avalanches. False avalanches are also associated with so-called after-pulsing. Charge trapped when an intense avalanche current runs through the device will be spontaneously released later over a period of several microseconds. False avalanches triggered without the detection of a photon, whether by noise or after-pulsing, create errors during quantum key distribution protocols.

The quest for high-speed, high-efficiency, low-noise and low-after-pulsing detectors has found a solution in superconducting nanowire detectors. Developed originally as hot-electron bolometers for microwave- and radio-astronomy applications, superconducting detectors have demonstrated high-speed operation with very low levels of dark current when adapted for optical measurements. When a photon is absorbed by a thin and narrow superconducting NbN nanowire, maintained at a temperature of around 4 K, it creates a localized region that has increased resistivity, a so-called hot spot[5]. The super-current gets pushed out from the hot spot into side regions where it exceeds the critical current density, thereby initiating the appearance of a resistive barrier across the entire cross-section of the nanowire. This, in turn, gives rise to a voltage pulse. Superconducting detectors are sensitive continuously from the visible to the mid-infrared region because of the small energy bandgap of NbN, which is several orders of magnitude smaller than the typical bandgap in semiconductors. This feature plus a much higher detection rate, low jitter and an absence of after-pulsing mean that SSPDs are of particular importance for quantum-communication and quantum-information applications. The very first use of such detectors in a practical quantum-cryptography system demonstrated a significant enhancement in the rate of reliable single-photon detection and dramatically reduced the rate of errors due to noise in the detector[6]. This manifested itself in an immediate increase in the distance over which reliable quantum key distribution was possible.

The principal limitation in quantum cryptography is associated with the situation where the optical state that is being used to encode the quantum bit is made up of more than one photon. This enables an eavesdropper to split the pulse energy and to keep a copy of the state without being detected, thus effectively bypassing the quantum no-cloning principle that is at the heart of quantum cryptography. The only way to isolate such events of multiphoton generation and to avoid a security breach is to use a PNR detector for controlling the single-photon purity of a quantum state.

The problem was originally approached using correlation measurements with single-photon detectors and linear optical elements such as beam splitters[7]. This allowed researchers to evaluate the percentage of events where there was more than one photon by comparing the rate of coincident double, triple, and other multiple detections (Fig. 1a). Another approach to PNR has been built around a special cryogenic semiconductor structure known as a visible-light photon counter[8]. Unfortunately, its operation is limited to the visible spectrum only. The first broadband PNR detection with superconductors was demonstrated using transition-edge-sensor technology[9]. This is basically a microcalorimeter with an output signal that is directly proportional to the total energy of photons absorbed in a tungsten nanofilm. The high PNR capability of a transition-edge sensor has, unfortunately, been accompanied by a rather low operation speed because of the slow reset process based on thermal cooling.

Now Divochiy *et al.* have taken an alternative approach by developing a parallel-connected integrated multi-unit device that has a compact footprint and is compatible with light delivery to its surface by a single optical fibre[2]. When an optical state consisting of several photons arrives at the device, it can trigger several detectors, producing an electrical pulse with an amplitude that is directly proportional to the number of photons arriving (Fig. 1b). This approach benefits from all the advantages associated with superconducting nanowire technology, such as a high speed of detection, low jitter and the absence of after-pulsing. It provides a PNR detector that enables direct characterization of photon-number statistics of light from fast sources, including quantum dots, at telecom wavelengths.

The fact that the efficiency at which photons are absorbed (quantum efficiency) is lower than in semiconductor APDs has always been an issue with SSPD detectors. However, the recent success of researchers at the Massachusetts Institute of Technology in constructing optical cavities around a superconducting nanowire detector has demonstrated that this problem can be effectively alleviated[10].

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