Superconductor photonics

The fields of metamaterials and plasmonics are both set to benefit from the use of superconducting materials.

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Superconductors — a fascinating family of materials discovered about a century ago that exhibit an electrical resistivity that vanishes at a sufficiently low temperature — are now creating exciting opportunities in photonics. In particular, their use in low-loss plasmonic waveguides and metamaterials, artificial structures patterned on a sub-wavelength scale that have customizable electromagnetic properties, is an exciting burgeoning research avenue.

The zero d.c. and low transient-frequency resistances of superconductors mean that they offer a promising alternative to the lossy conventional metals, such as gold and silver, that are normally used in metamaterials. However, it is important to note that superconductors can only be exploited in metamaterials and waveguide structures operating at terahertz or lower frequencies — at higher frequencies the energy of incident photons is sufficient to break the material’s Cooper pairs, destroying the superconductivity.

Importantly, superconductors behave like true plasmonic materials — their electromagnetic response is derived from their Cooper pairs, which have analogous behaviour to that of electrons in plasmonic metals at optical frequencies. Superconducting metamaterials can be highly tunable as superconductivity is strongly affected by a wide variety of parameters such as magnetic field, temperature, light and applied current.

In recent years, several research groups working on superconducting metamaterials have observed a variety of rich and useful phenomena including sharp resonances, electromagnetically induced transparency (EIT), toroidal dipolar resonances, strong nonlinearity and quantum interference effects.

In particular, the creation and control of resonances is useful in many applications where superconducting metamaterials could excel. For example, a compact spiral high-temperature superconducting ‘meta-atom’ with a resonance frequency of approximately 50 MHz has been reported with a quality factor (Q-factor, a measure of the sharpness of a resonance) of up to 30,000 at 70 K (ref. 2). Such high Q-factors are well beyond the capabilities of metamaterials based on conventional metals. Sharp responses are also known to arise in the regime of EIT — a coherent quantum phenomenon that occurs in an absorbing atomic vapour when a pump beam is used to create a temporary transmission window for a probe beam that shares the same excited state. Destructive interference of quantum probability amplitudes between energy states inhibits absorption and leads to a narrow Fano-like transmission resonance and a dramatic reduction in the group velocity of the otherwise opaque atomic medium. As a result, the probe pulses can be strongly delayed and propagate without losses.

EIT-like behaviour is also possible in metamaterials. It was first observed in the Fano-like response of metamaterial arrays consisting of asymmetric metallic split rings. It was then studied in superconducting YBCO split ring arrays and complementary slit metamaterials demonstrating temperature-dependent transmission resonances in the sub-THz (ref. 5) and THz (refs 6 and 7) frequency ranges.

Asymmetric split ring metamaterials, breaking the symmetry leads to two arcs of the ring. When excited by an incident electromagnetic wave, the two arcs support currents oscillating in-phase, but for a narrow excitation frequency range an antisymmetric current configuration is established due to the coupling of the two resonances. This creates a narrow transparency window in the transmission spectrum of the metamaterial. Such resonances can be adjusted via either the temperature of the superconductor metamaterial or the asymmetry of the design.

Superconductor EIT metamaterials may lead to the development of a new breed of thermally tunable slow-light devices and temperature sensors. Temperature control of superconductors could be used in very low threshold nonlinear devices where a huge nonlinearity and intensity-dependent transmission is possible for incident field intensities of just a few milliwatts per square centimetre.

Metamaterials made from superconducting niobium film can feature a nonlinearity that is much higher than that achievable in natural media, including liquid crystals. The device employed by Savinov et al., wires forming the meta-atoms were fabricated with nanoscale...
constrictions to increase the current density and to create a highly localized dissipation of Joule heat by the currents induced by the incident radiation (Fig. 1a).

Superconducting metamaterials are also used as platforms for investigating new physics. In recent work reported at this year’s CLEO conference in San Jose, California, USA, YBCO planar superconductor metamaterials have been used to demonstrate a strong toroidal dipolar response. Toroidal dipole excitations are attracting the interest of the research community due to their unusual properties. In particular, it has been shown that the strength of their interaction with electric and magnetic fields depends not on the strength of the fields, but rather on their time derivatives. Some researchers also argue that toroidal excitations can generate oscillating vector potentials in the absence of electromagnetic fields.

The toroidal dipole is a fundamental electromagnetic excitation; it is a part of the extended family of multipoles. Toroidal dipolar resonances — a useful property for many applications. It is perhaps apt that the classical experimental set-up used in metamaterials research — the split ring meta-atom resonator — has much in common with a fundamental unit of superconductivity — the Josephson junction ring. A two-dimensional array of superconducting Josephson rings, each of which can be considered a macroscopic meta-atom, is truly a quantum metamaterial. By mimicking natural materials, this is the next step from the array of conventional metallic meta-atoms supporting classical plasmonic resonances. Indeed, metamaterials based on superconducting quantum interference devices (SQUIDs) have now emerged as a popular direction for experimental research.

Replacing the capacitive gap of the split-ring resonator with a Josephson junction introduces strong nonlinearity in the system and offers low dissipation and remarkable high-bandwidth tunability with the application of small d.c. magnetic fields, radiofrequency currents or temperature variations. The SQUID metamaterial creates low-loss tunable devices for controlling electromagnetic radiation at the quantum level, in magnetic-flux sensing and for the design of low-noise amplifiers for radiofrequency sensing and qubit readout.

Beyond the metamaterial applications described above, superconductors also provide a new platform for creating long, low-loss plasmonic waveguides for guiding sub-THz and THz frequency radiation. To date, much research involving plasmonics has focused on the optical part of the electromagnetic spectrum (where losses are the main challenge), but the use of low-loss superconductors allows access to the THz and sub-THz bands. This could include the development of data processing circuitry though the integration of highly efficient broadband superconducting metamaterial switching devices with low-loss superconducting waveguide interconnects and compact THz quantum cascade emitters. The widespread application of superconductor devices would not be hindered by the low-temperature operation requirement since commercially available compact cryogenic coolers are already widely used in medical diagnostic, sensor and telecommunications equipment.

References

12. Alexander B. Khanikaev and Andrea Alù

In the quest for on-chip optical isolation, scientists demonstrate non-reciprocal optical response based on a ‘synthetic’ magnetic field in an all-silicon platform. This may open directions to optical routing, on-chip lasers and integrated nanophotonic signal processing.

Alexander B. Khanikaev and Andrea Alù

In contrast with our everyday knowledge that eggs can be easily turned into an omelette but not vice versa, the basic laws of physics are typically indifferent to the direction of time flow, that is, physical processes are often reversible and are said to be ‘reciprocal’. For instance, to determine if we can be heard through a wall, we can simply check if we can hear through it. In optics this property is formally described by the Lorentz reciprocity theorem, which directly follows from Maxwell’s equations in linear materials that obey ‘time-reversal’ symmetry and states that, if one reverses the propagation direction of a light wave, the overall transmission properties are unaffected.

Optical isolators — diodes for light that allow photons to travel in one direction but prohibit reverse propagation — are crucial devices for routing signals in optical fibre networks and for providing stability in laser operation. Commercially available optical isolators are based on magnetically biased ferromagnetic materials. However, because of the weak character of magnetooptical effects, they typically include bulky optical components that are difficult to integrate with a nanophotonic platform. To achieve non-reciprocity without...