Background

A sideband is a band of frequencies higher than or lower than the carrier frequency, containing power because of the modulation process. When a monochromatic electromagnetic (EM) wave ($\omega_0$) is dynamically modulated with frequency $\Omega \ll \omega_0$, new frequencies (sidebands) $\omega_n = \omega_0 + n\Omega$ ($n \in \mathbb{Z}$) are generated in the spectral domain. Sideband generation is a fundamental process that occurs in various systems, from the atomic level to macroscopic level, where dynamic modulation of EM waves exists. The sidebands carry the information (modulation) transmitted by the signal. The sidebands consist of all the Fourier components of the modulated signal, except the carrier, and all forms of modulation produce sidebands.

Huygens’ metasurfaces allow almost arbitrary wave front shaping, however, dynamic and arbitrary control of the amplitude and phase response remains problematic. ANU and UNSW researchers have solved this problem by exploiting the parametric process in a time-varying Huygens’ meta-device. The meta-device is made of both electric and magnetic meta-units with independently controlled modulation, and the phase of this modulation is imprinted on the scattered parametric waves (sidebands), controlling their shapes and directions. Using optimised modulation signals, a high conversion efficiency (>75%) from the carrier wave to the target sidebands is achieved and the sideband scatterings are fully controlled by amplitude and phase of modulation. The meta-device offers unique features in controlling wave scattering.

Firstly, since the relative modulation phase can be tuned to different values at different unit cells, it provides a new opportunity to generate a phase gradient among the metasurface, and phase at each unit cell can be dynamically tuned over a $2\pi$ regime. Secondly, the directionality of the sidebands can be actively tuned by changing the modulation phase difference in the electric and magnetic meta-units, meaning that the meta-device can function as a transmissive or reflective device on the same structure. Manipulation of sidebands in the aforementioned ways is particularly attractive and of great importance for a wide range of applications. For instance, a number of optical systems with dynamic...
modulation rely on sideband control, e.g. sideband cooling and magnet-free optical isolation\(^1\). Time-modulated linear arrays (TMAs) also rely on the ability to generate multiple beams at different sidesbands, with different shapes and features, for use in multi-function radars, direction finding, and in mobile wireless communication. Our meta-device is a first of its kind, in that it is arbitrarily tunable and can direct EM waves towards any direction or control multiple beams to perform different functions at the same time. Combined with the ability to achieve high conversation efficiency of the sidesbands means that this device could lead to a new class of ultra-compact devices relying on dynamic modulations of EM waves.

**Potential applications & current challenges**

Sidebands are controlled in a number of current day applications, with other types of opto-electrical or optical devices, but none utilising a time-varying meta-device. General advantages of a metasurface-based system are that it has a low hardware cost, low energy consumption and a simplistic structure – meaning that ultra-compact, tunable devices with novel functionalities can be designed, e.g. compact isolators, beam deflectors or radar sensors.

An isolator is a 2-port device that transmits microwave or RF power in one direction only. It is used to shield equipment on its input side, from the effects of conditions on its output side, e.g. to prevent a microwave source being detuned by a mismatched load\(^2\). Current microwave isolators are made from magnetic materials, which are expensive and bulky. Isolators are typically used as a circuit component for a circulator (3-port ferromagnetic device used to regulate the signal flow within a circuit). In radar systems, circulators are used as a type of duplexer to route signals from the antenna to the receiver, without allowing the signals to pass directly from transmitter to receiver\(^2\). Although ferromagnetic circulators can provide good forward signal circulation whilst suppressing greatly the reverse circulation, their major shortcomings, especially at low frequencies, are their bulky sizes and narrow bandwidths\(^2\). Other circuit issues are the power limitation and the signal-to-noise degradation, which are critical when it is used as a duplexer for sustaining the strong transmit power and clean reception of the signal from an antenna\(^2\).

Advanced driver-assistance systems (or ADAS) can be grouped into three major categories: those that aid the driver, those that warn the driver and those that assist the driver in performing certain basic driving functions\(^3\). Many ADAS systems use radar technology. Some of the reasons for using radar technology in the automotive sector are (i) detect moving or static vehicles, (ii) add value to safety, comfort and assistance features of automobiles, (iii) reduce the fatigue rate globally, and (iv) monitor vehicle speed in all-weather conditions\(^3\). The major players in the ADAS market are increasingly focusing on technological advancements for the development of superior quality and smaller sized radar systems\(^3\). Current automotive radar systems are based on FMCW (frequency modulated continuous wave) radar, which varies the signal source to sequentially and spatially scan from different directions. Using our meta-device the signal source is converted into multiple beams (sidesbands at different frequencies) which can simultaneously scan from different directions, enabling the detection of objects at multiple angles simultaneously, resulting in the quicker and more sensitive detection of surrounding objects. This functionality, combined with the meta-device’s miniaturisation will facilitate the development of more compact, sensitive, safer sensors for automobiles.

Wireless services demanding more mobility, capacity, and robustness have placed wireless communications as the fastest growing sector of the telecommunications industry. As a result, the increasingly limited wireless medium has to be smartly exploited and antennas are called to play an important role to achieve such a goal. TMAs, also known as four-dimensional antenna arrays, introduce time as an additional dimension for generating ultra-low sidelobes and realising real-time beam scanning by harmonic components\(^4\). Sideband radiation suppression, enhancement of power efficiencies and the incorporation of harmonic components are being explored to improve the existing TMAs or promote the practical application of TMAs\(^4\). To suppress the sideband radiation, a method using non-uniform periodical modulation is used. This method has an advantage of low computation and can be easily used for synthesising a real-time radiation pattern according to the environmental need\(^4\). Ultimately TMAs mostly focus on the antenna problem (signal emission or receive) whereas our meta-device can deal with the more general problem of interacting with an incoming EM wave and redirecting it within the environment as desired. Unlike TMAs, our meta-device can control the directionality of a scattered EM wave from forward to backward, and can interact with the free-space waves with high efficiency. In addition, the meta-device has subwavelength inter-element spacing enabling a much larger angle range for beam steering and higher quality for complex beam forming without introducing large sidelobes. Moreover, there is an increasing demand by industry to make antennas more compact, to limit the power needed to communicate\(^6\). However, this in turn has a negative impact on bandwidth (the bandwidth in which the antenna can receive and transmit\(^6\)). By combining our meta-device, with a signal feeding arrangement and antenna phased array, it is possible to prevent the limitation in antenna bandwidth for compact antennas. Structurally the antenna could be flat, electrically controlled (rather than manually controlled), miniaturised (currently phases array applications are bulky as they require the use of phase shifters and phase splitters etc.) and programmable to work within the 3-10 GHz band.

![Figure 1: Schematic of time-varying Huygens’ meta-device for parametric waves: (a) by independently modulating the electric and magnetic polarizations P and M at each unit, the sid eband scattering can be manipulated almost arbitrarily; (b) design of a time-varying Huygens’ unit working around 3.7 GHz inside a WR229 waveguide (sizes in mm): x\(_M\)=7.8, y\(_M\)=12, x\(_E\)=14.25, y\(_E\)=6, w\(_E\)=3.89, and d=6.5. The track width and gap size are both 1 mm. The electric and magnetic meta-units are printed separately on 0.4 mm-thick Rogers4003 substrates. Varactor diodes (SMV 1405) are employed as tunable capacitors.](image-url)
capacitance based on changes in reverse-diodes (voltage-tunable capacitors that vary are individually modulated via the varactor and magnetic meta-units. The meta-units relative modulation phase of the electric the sidebands are then controlled by the directionality (transmissive or reflective) of waveform) by the metasurface and the efficiency - dependent on the modulation into sidebands (conversion with high Huygens’ metasurface simultaneously. The dynamic Huygens’ metasurface consists of both electric and magnetic meta-units with independently controlled modulation via external stimuli (Figure 1)\(^1\). Modulation is the process of varying one or more properties of a periodic waveform (i.e. the high-frequency carrier wave) with a low-frequency modulating signal (i.e. the modulation waveform). A genetic algorithm is employed to (i) optimise the modulation waveform in order to maximise both directivity and the power of the desirable sidebands and (ii) introduce higher order correction terms in the modulation waveform to suppress the undesirable high order sidebands. Different types of sideband generation require very different modulation waveforms (Figure 2)\(^1\). Thus, two signals (carrier wave and modulation waveform) interact with the dynamic Huygens’ metasurface simultaneously. The carrier frequency is converted into sidebands (conversion with high efficiency - dependent on the modulation waveform) by the metasurface and the directionality (transmissive or reflective) of the sidebands are then controlled by the relative modulation phase of the electric and magnetic meta-units. The meta-units are individually modulated via the varactor diodes (voltage-tunable capacitors that vary capacitance based on changes in reverse-bias voltage) and the relative modulation phase of the meta-units is dictated by the modulation waveform. Since the phase of the sideband is controlled by the modulation phase, a modulation phase gradient along the metasurface enables control of the steering angle or the scattering pattern of sidebands, including steering of beams heading in the reverse direction (so there is 360° control), or performing different functionalities at different sidebands (Figure 3)\(^1\).

**Advantages**

- **Compact:** Provides spatial control (not spectral control) of sidebands using a compact resonant device
- **Frequency-demultiplexed functionality:** Can scatter different sidebands in different directions or in different patterns
- **Switching of directionality:** Can change sideband directionality on the same device, i.e. can function as a transmissive or reflective device
- **Huge steering angle:** Can achieve 360° sideband beam control/steering
- **Flexible frequency bands:** Can be designed to work over several frequency bands (currently designed to work within the microwave band)
- **High power conversation efficiency:** Highly efficient sideband conversation (>75%)
- **One feed source:** Only have to use one feed source, rather than multiple sources for applications such as radar sensing and phased array antenna

**Market**

RF semiconductor devices are key components of wireless and wired communication systems. RF power devices include amplifiers, passives, switches, duplexers and isolators. The global RF power semiconductor market was valued at (USD) $10.6 billion in 2015 and is expected to reach $31.3 billion by 2022 (CAGR = 15.4%)\(^2\). The market growth is attributed to the increased use of RF power devices in applications such as smartphones and automobiles\(^2\). This industry needs innovations to develop cost-effective and more efficient devices to support RF power applications. There is a high level of design complexity in RF power devices. The major challenge for designers is to achieve between efficiency whilst keeping the cost low and the structure less complex\(^2\). Although the RF power semiconductor market is mature, the R&D phase is significant, as it requires a number of innovations to develop a competitive, marketable product\(^2\).

The global radar systems market was valued at (USD) $20.3 billion in 2016 and is projected to grow at a CAGR of 5.4%, reaching $26.4 billion by 2021\(^3\). Among the sub-segments of commercial application, the automotive sub-segment is projected to grow at the highest rate (CAGR of 10.9%) during the forecast period, growing from a value of $2.1 billion in 2016 to $3.4 billion by 2021\(^3\). The increasing opportunities for radar technology in driverless or self-driving cars is expected to boost this market. This technology is still at its nascent stage.

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**Figure 2:** Sideband scattering: (a-c) measured sideband spectra of three different types of sideband scattering; \(n^2/n_m\) is the normalized scattered power (over all the sidebands) of the \(n\)th order sideband in the forward (backward) direction; (d-f) the corresponding modulation signals are plotted. \(\phi_m - \phi_E\), the directionality of sideband scattering can be tuned between forward and backward mode while keeping the efficiency unchanged.

**Figure 3:** (a) Photograph of the time-varying Huygens’ array; (b) the measured 360° beam steering of sideband using the time-varying Huygens’ array; (c) measured nearfield distribution of the sidebands. Using the same modulation phase pattern, the time-varying array acts as a defocusing lens for the -1st order sideband, and simultaneously a focusing lens for the 1st order sideband.
but manufacturers of self-driving cars are expected to launch this form of automobile automation by 2020, with radar systems playing a major role\textsuperscript{6}. Commercial radars are deployed in private ships, as well as in railways, civil aviation and other means of transportation. Commercial radars are also used for security and surveillance applications, such as industrial alarms and door openers, weather monitoring of agricultural industry, construction industry, high tech electronic devices manufacturing, and robotics automation process\textsuperscript{6}. The global ADAS market was estimated to be (USD) $25.8 billion in 2016 and is predicted to reach $42.4 billion by 2021, growing at a CAGR of 10.4\%. Radar sensor technology is estimated to dominate the ADAS market (by sensor technology) owing to its ease of operation and cost-effectiveness. Radar sensor technology within the ADAS market is expected to grow from $14.0 billion in 2016 to $22.9 billion by 2021 at a CAGR of 10.4\% (equalling 54.2\% of the global ADAS market share in 2016)\textsuperscript{6}. The number of radar sensor units will increase from 87.9 million units in 2016, to a predicted 142.0 million units in 2021, at a CAGR of 10.1\%.\textsuperscript{6} The drivers of this market include growing concerns and government regulations pertaining to safety and an increased demand for premium vehicles.

The global metamaterial market was valued at (USD) $20.3 million in 2015 and will be worth $643.0 million by 2025, growing at a CAGR of 41.3\%.\textsuperscript{5} Applications include aerospace, defence, medical instrumentation, optics, sensing and telecommunication. Metamaterials are currently being used only in the microwave region of the EM spectrum, as it is easy to fabricate metamaterial-based devices at these wavelengths. R&D is being carried out continuously to use metamaterials in other regions of the EM spectrum (such as the visible region) or in more than one region simultaneously. EM metamaterials are expected to dominate the overall metamaterials market between 2015-2025\textsuperscript{5}. Two major factors responsible for this are (i) they are easy to develop as the technologies needed to fabricate them are already available, and (ii) there is a growing trend to use them in antennas. Conventional antennas that offer high transmission and reception efficiency have very large dimensions, which seems to be a disadvantage in the aerospace and defence sector\textsuperscript{5}. This is because the cross section of airplanes and satellites today are decreasing and as such, it is impossible to install such large antennas on them. Metamaterial-based antennas offer the same efficiency with small cross-sectional areas and are easier to install on airplanes and satellites\textsuperscript{5}.

Opportunity

ANU is seeking engagement with prospective industry partners and/or licensees interested in establishing a collaboration for the future development and/or bringing-to-market this time-varying meta-device. ANU is well-placed to work with partners to optimise the meta-device for their specification application and functionality requirements.

Patent status

The IP is owned by ANU and has a priority date of the 18th August 2017. The provisional patent was progressed to PCT in 2018 and is due to enter National Phase filing in 2020. The Technology Readiness Level is 2 - we currently have a lab but not industry proof of concept (i.e. a fundamental prototype). We recently up-scaled the metasurface from a pair of meta-units to an array of meta-units and are looking to collaborate with industrial partners to explore the full potential of this array in practical applications.

Scientific team

Dr Mingkai Liu:

Dr Liu is a Fellow at the Nonlinear Physics Centre (NLPC) within the Research School of Physics and Engineering (RSPE) at ANU. Dr Liu has a great deal of expertise in working with metamaterials and is engaged in fundamental research on various novel linear and nonlinear phenomena in metamaterials and metasurfaces, over a wide range of frequencies from microwave to terahertz to optics. In particular, his past experiences with designing tunable metamaterials, time-varying metasurfaces, meta-liquid crystals, and magnetoelastic metamaterials, makes him a valuable member of the team.

Prof Ilya Shadrivov:

Prof Shadrivov is the leader of the microwave and terahertz group at the NLPC within the RSPE at ANU. A recipient of the prestigious Future Fellowship, Prof Shadrivov works in the areas of classical and physical optics, microwave and millimetre wave theory and technology, nonlinear optics and spectroscopy, and electrostatics and electrodynamics. Prof Shadrivov received his PhD in Physics and brings both strong theoretical and experimental expertise to the team, particularly in the fields of designing tunable metamaterials and advanced optical materials.

Dr David Powell:

Dr Powell is a Senior Lecturer at The University of New South Wales (UNSW) within the School of Engineering and Information Technology. Dr Powell has worked with metamaterials and is an expert on numerical techniques for modelling metamaterials and nanophotonic structures. Dr Powell brings to the team strong analytical expertise in modelling and optimising the near-field interaction of individual meta-units, combined with a strong experimental background in microwave and terahertz experiments, particularly in the field of non-linear and tunable metamaterials.

Contact

Dr Fiona Nelms
Director, Technology Transfer Office
T  +61 2 6125 9187
E  fiona.nelms@anu.edu.au
W  www.anu.edu.au/research/innovation

References


\textsuperscript{2}MarketsandMarkets (2016) RF power semiconductor market by product (amplifiers, passives, switches and dupplexers), material (Si, GaN, GaAs), frequency, application and geography – global forecast to 2022. Market report accessed April 2017.


