Low Power Metasurface Beamforming Antennas with Dynamic Polarization Control for Multi-Orbit Satcoms

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***Abstract*—Mobile satcoms is evolving in a similar way to terrestrial mobile communications, whereby bespoke user terminal hardware operating on proprietary networks is transitioning to multi-orbit, multi-network hardware that can roam across different satellite constellations. A key enabler for this capability is polarization agility at the user terminal antenna. Metasurface technology provides this functionality with the lowest power consumption available when compared to other types of electronically scanned antennas. The low power consumption afforded by metasurface technology is an essential feature for mobile platforms like the consumer automobile, where satellite roaming will be a hard requirement.**

Keywords—metasurfaces, satcom, multi-orbit, phased arrays, shared aperture

I. Introduction

The satellite communications ecosystem is undergoing a fundamental transformation driven by the disruption created by cheaper access to space and the emergence of low Earth orbit (LEO) satellite constellations such as Starlink, OneWeb, Amazon Kuiper, and Telesat Lightspeed. However, each of these constellations represents a proprietary network accessed by bespoke user terminal (UT) hardware. Comparatively, the situation with satellite communications is analogous to 2G cellular networks (e.g. CDMA, GSM, etc.). The future state of satellite communications will evolve to a standards-based approach where user terminal hardware will interoperate and roam across LEO, mid Earth Orbit (MEO), and geostationary orbit (GEO) satellite networks. Given that satellite networks leverage polarization diversity for frequency reuse, the UT antenna technology must support polarization agility to achieve interoperability.

While recent advancements in phased array technology have led to an optimum integration of beamformer and frontend ICs with required array densities, compromises are typically made, such as fixed polarization and/or limited scan range, to control power consumption and cost. By doing so, however, these compromises restrict the design to a specific satellite network and/or fixed use cases (as opposed to mobile use cases). A phased array antenna designed for both mobility and polarization agility tends to have high power consumption, associated thermal management issues, and high cost.

Metasurface antennas on the other hand provide design flexibilities that make them excellent candidates for advanced capabilities such as polarization agility, wide scan angle (for mobile applications) and multi-orbit interoperability. Kymeta has recently introduced a satcom terminal that uses a full duplex, shared aperture antenna with the ability to switch between LEO and GEO networks leveraging a polarization agile design. This paper delves into the fundamental characteristics and operational principles of metasurface antennas, highlighting their unique attributes that make them ideally suited for multi-network satellite communication terminals. Furthermore, we elucidate the distinct advantages of metasurface antennas over phased arrays in terms of design flexibility, scalability, and performance across mobile operating scenarios. Lastly, we present experimental results demonstrating the practical feasibility and efficacy of integrating metasurface antennas into real-world mobile satellite communication systems.

II. Diffractive Metasurface Antennas

A. General Design Aspects

A metasurface antenna is a passive aperture antenna that consists of periodically arranged and resonant scattering elements. These elements are subwavelength in both their size and spacing. By exciting the metasurface elements with a guided feed wave a desired radiated field can be achieved. The resonant frequency of each element in the array is individually controllable. Individual element control enables the metasurface to arbitrarily shape and form the radiated wave from the aperture, thereby producing the desired far field radiation pattern. Fully electronic beam scanning in 360° of azimuth, 15°-90° elevation, and switchable polarization control from tracking linear to circular polarization (right hand CP or left hand CP) is achieved.

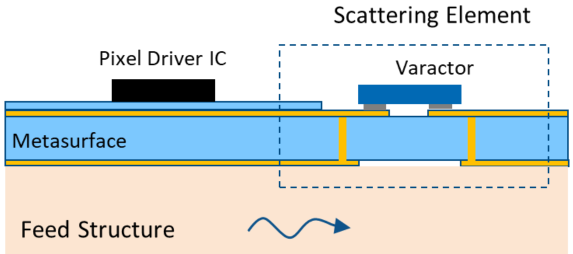

Fig. 1. Schematic cross section of a metasurface scattering element

Fig. 1 presents a schematic cross section of a metasurface scattering element where the resonant frequency (and thereby scattering strength and phase) is controlled through voltage applied to a varactor diode.

The feed structure represents a very low-loss (~0.5-0.85 dB) distribution network for the metasurface and consists of a simple parallel plate waveguide. The metasurface forms the upper conducting wall of the waveguide, where each scattering element consists of a slot etched into the upper conductor. This feed mechanism also has the advantage of being very broadband due to the TEM nature of the parallel plate waveguide. We have demonstrated shared-aperture, full duplex antennas in both the Ku satcom bands (10.7-14.5 GHz), and Ka satcom bands (17.7-31 GHz) with this approach. In the Ka design we achieved a return loss of better than 15 dB across the entire band (a 55% fractional bandwidth) [2].

Each unit cell of the metasurface consists of an orthogonal pair of adjacent slots that have ± 45° rotation with respect to the direction of the feed wave propagation. The element geometry in conjunction with the subwavelength spacing (typically ~λ/6) permits independent control of the Lorentzian amplitude and phase, resulting in arbitrary modulation pattern synthesis on the metasurface. Full control over frequency, polarization, and beam scanning angles can be achieved within the tunable bandwidth obtained by the scattering element. Fig. 2 depicts a Ku-band varactor-controlled metasurface.

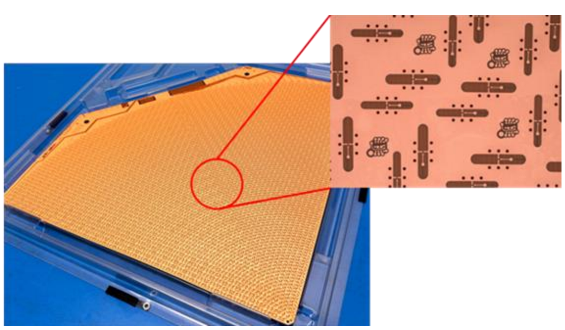

Fig. 2. Full duplex varactor-tuned metasurface in the Ku satcom band with interleaved Rx and Tx subarrays

B. Holographic Beamforming and Polarization Control

The tuning state of each element in the array (referred to as the modulation pattern) is determined through a holographic interference principle. In this formalism, the feed wave is analogous to a reference beam in optical holography (1). The wave off of the surface of the antenna is analogous to the object beam (2). The metasurface acts as a dynamically reconfigurable diffraction grating, where the diffraction pattern is determined by the interference of these two waves [1]:

$$\Psi_{ref}(d) \approx exp\left(-i\vec{K}_s \cdot \vec{d}\right) \quad (1)$$

$$\Psi_{obj}(\vec{r}, \theta_o, \phi_o) = exp\left(-i\vec{K}_f(\theta_o, \phi_o) \cdot \vec{r}\right) \quad (2)$$

$$\Psi_{intf} = \Psi_{obj}\Psi^{*}_{ref} \quad (3)$$

In the equations above, $\vec{K}_s$ is the feed wave wavenumber, $\vec{K}_f$ is the free space wavenumber, which is a function of the desired azimuth and elevation scan angles, frequency, and polarization, and * denotes the complex conjugate.

Fig. 3 depicts the holographic modulation pattern calculated from equations (1)-(3) for a cylindrical geometry. The left figure shows the metasurface and scattering elements and the right figure shows the calculated diffraction pattern.

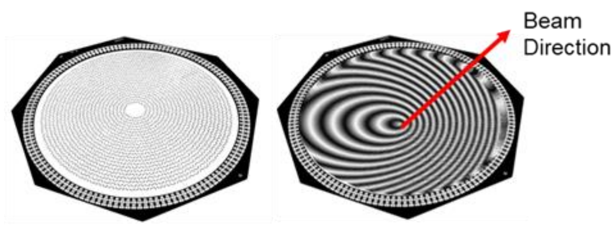

Fig. 3. Diffraction pattern on a cylindrical metasurface

Polarization is controlled dynamically on the array through software by controlling the voltage state and resultant Lorentzian amplitude and phase on each individual scattering element. An example is provided in Fig. 4. On the left the orthogonal element pair is tuned to the same amplitude and phase, with the resultant E-field vector being the sum of the individual E-field vectors of the two orthogonal elements. On the right, one element is tuned to scatter a lesser amplitude, but equal phase as the other element, thereby rotating the resultant E-field vector. Circular polarization is obtained by exciting alternating rings of elements that are orthogonal and 90° out of phase.

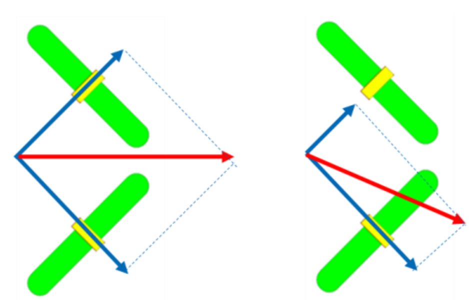

Fig. 4. Resultant E-field vectors from an equivalent modulation state (left) and rotated modulation state (right)

Stepping back to look at the modulation pattern on the entire array, Fig. 5 provides the diffraction patterns for a broadside beam with linear, right hand circular, and left hand circular polarization. One can observe the direction of the spiral in the diffraction pattern change direction between the right and left hand CP patterns.

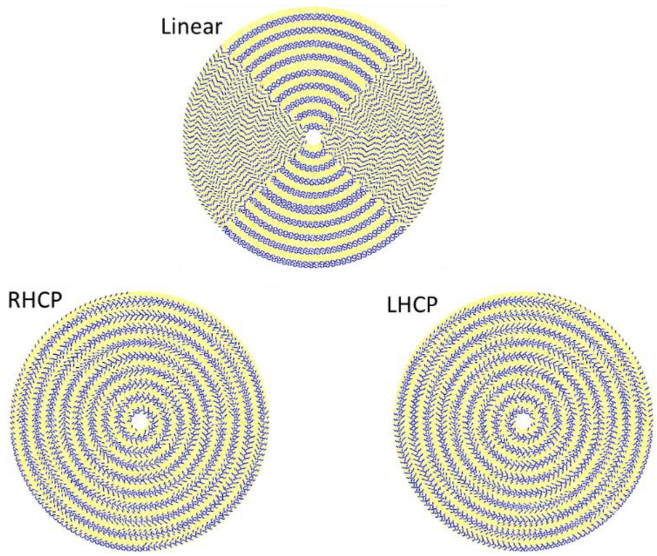

Fig. 5. Example metasurface diffraction patterns for different far field polarization states

C. Control Mechanism

Given the dense spatial oversampling of the aperture relative to the typical λ/2 Nyquist condition direct addressing of each antenna element is not practical with common planar manufacturing techniques (e.g. printed circuit board or flat panel thin film-on-glass). Therefore, we employ an active matrix addressing scheme, equivalent to liquid crystal display and other flat panel display technologies [2]. In this approach a series of column lines provide the desired varactor voltages and changes to the column line voltages are synchronized with activating a specific row of elements. All other rows are kept off, thus only the desired row of elements is biased to the voltages on the column lines. The array is then refreshed row-by-row. A simple FET switch is used at each element to activate each row. Fig. 6 shows a photograph of the metasurface with 4-channel pixel drivers that implement the FET switches for the active matrix.

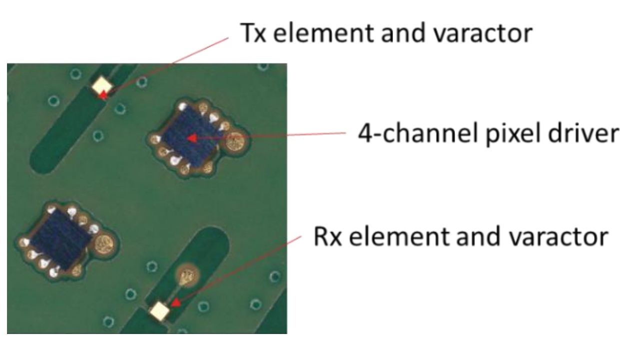

Fig. 6. Ku-band varactor metasurface with discrete pixel drivers implementing the active-matrix backplane control

III. Results

Antenna performance results for the metasurface antenna are shown in the following figures. Note that the results presented below pertain to Kymeta's currently fielded product based on a liquid crystal tuned metasurface. Also note that the results are shown for the antenna operating in full duplex mode, with the Rx and Tx subarrays operating simultaneously.

Fig. 7. provides realized gain as a function of scan angle for three different polarization states in the Ku Rx band at 12.2 GHz. A cosine roll-off (CRO) exponent of 1.2 or better is achieved across each of the polarization states.

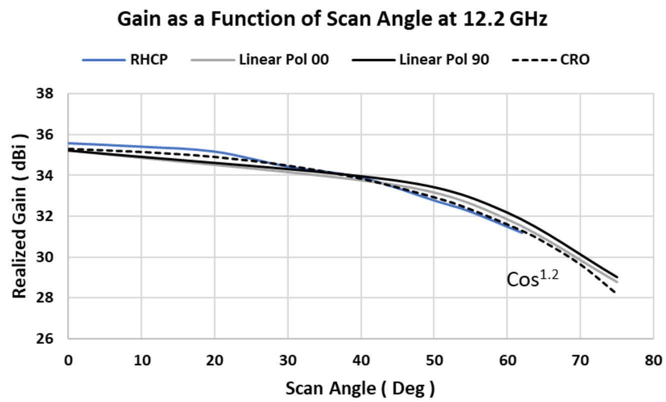

Fig.7. Realized gain as a function of scan angle for Horizontal, Vertical, and RHCP polarizations at 12.2 GHz. A CRO exponent of 1.2 is achieved.

Fig. 8 provides realized gain as a function of scan angle for three different polarizations states in the Ku Tx band at 14.2 GHz. The same CRO exponent of 1.2 is achieved at Tx.

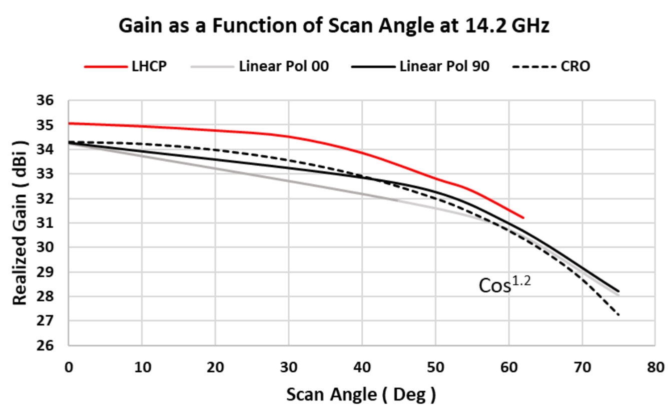

Fig. 8. Realized gain as a function of scan angle for Horizontal, Vertical, and LHCP polarizations at 14.2 GHz. A CRO exponent of 1.2 is achieved.

Fig. 9. provides the axial ratio as a function of scan angle for two different frequencies in the Ku-Rx and Ku-Tx satcom bands, respectively. An extremely low axial ratio is achieved in the metasurface implementation after a calibration procedure. The calibration procedure involves compiling an optimized parameter set across a small population of production antennas, and then applying that parameter set across subsequent production antennas. Each production antenna receives a short optimization across a limited parameter set once the initial population of antennas is calibrated.

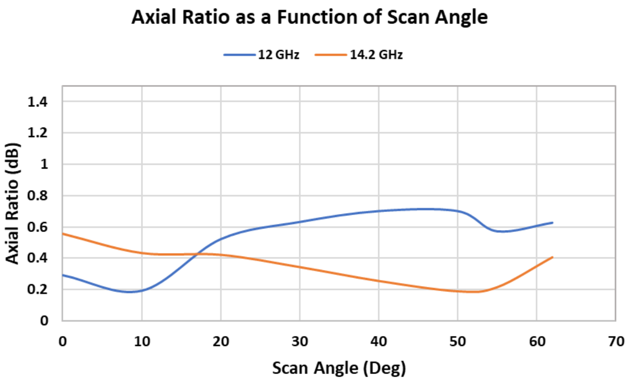

Fig. 9. Axial ratio as a function of scan angle at 12.0 GHz and 14.2 GHz.

IV. Comparison to Phased Array Design

Commercial satcom phased array solutions are typically represented by two design cases: 1) Full-duplex polarization agile; 2) Half-duplex fixed polarization. Half-duplex fixed polarization designs represent a trade off in capability to achieve minimum power consumption and cost. However, these phased arrays are bespoke to LEO constellations and cannot achieve LEO/MEO/GEO interoperability. On the other hand, full-duplex, polarization agile designs can adjust polarization as required to switch from different satellite constellations, but the number of feed points doubles, resulting in a doubling of the number of beamforming ICs and front-end ICs with associated increases in cost and power consumption.

Fig. 10 depicts a typical half-duplex, fixed polarization phased array element. In this architecture a T/R switch implements time division duplexing (TDD) between the transmit path and the receive path. At the antenna element, aperture coupling is typically used to implement fixed R/L CP on either of the receive and transmit paths.

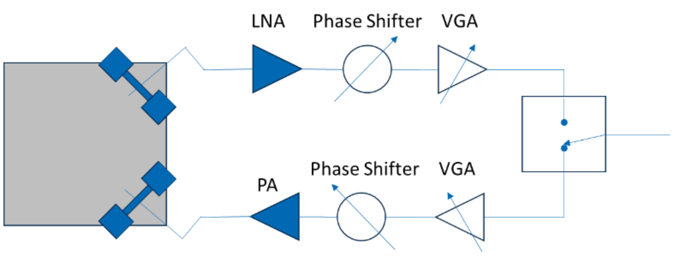

Fig. 10. A typical implementation of a fixed polarization, half-duplex phased array element and RF front end

Fig. 11 depicts a typical full duplex, polarization agile design. In this design, separate arrays are used for receive and transmit to resolve isolation problems. On each of the arrays dual beamformer and front-end IC channels are used to feed each antenna element in a dual polarization configuration. By adjusting phase and amplitude on each of the channels feeding the antenna element, polarization states from rotated linear to R/L CP can be achieved.

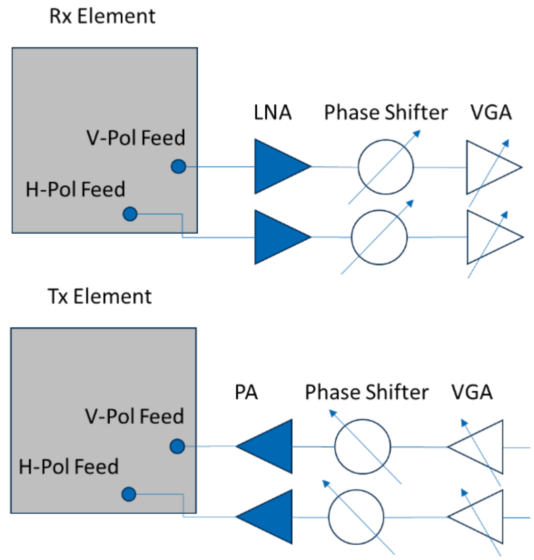

Fig. 11. Typical full duplex, polarization agile phased array front-end architecture

Fig. 12 shows an exploded 3D model of Kymeta's terminal construction. The design is a relatively simple stack up of several planar components, with the metasurface assembly sandwiched between the feed structure and radome. The control electronics and RF transceiver are placed on the back of the feed assembly, where the metasurface antenna is fed from a central feed point. The total nominal power consumption for the system is 200 Watts, with the metasurface beamforming layer only consuming 3-4 Watts. The antenna control unit, modems, and RF transceiver (block upconverting amplifier—BUC, and low noise block downconverter—LNB) draw the remaining 196 Watts.

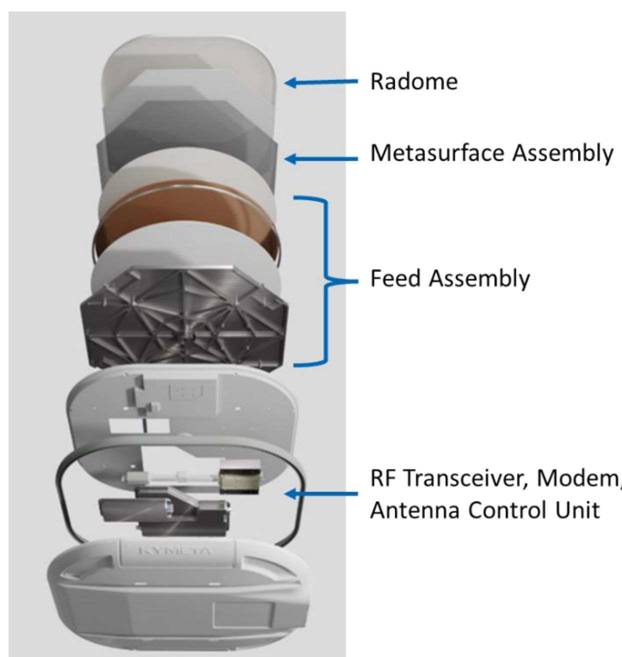

Fig. 12. Exploded diagram of the metasurface satcom terminal

Table 1 compares the total system power consumption across several different satcom terminal types. Data was compiled from publicly available specification sheets. Direct comparison is somewhat difficult due to differences in system configuration. Our multi-orbit terminal, for example, uses a 40-Watt high power amplifier achieving an EIRP of ~ 50 dBW and houses two separate modems for GEO military use cases. It is clear, however, that when comparing the multi-orbit capable terminals, the metasurface approach has significantly lower power consumption, and is nearly that of the LEO-only, fixed polarization phased array terminal.

TABLE 1. COMPARISON OF KU-BAND MULTI-ORBIT SATCOM USER TERMINAL NOMINAL POWER CONSUMPTION

Terminal Product	***Terminal Type***	***Power Consumption (W)***
Starlink HP [3]	Fixed-Pol PAA LEO only	110-150
GetSat Slingblade [4]	Pol Agile PAA Multi-orbit	700
Litecoms Cart* [5]	Pol Agile PAA Multi-orbit	640
This work	Metasurface Multi-orbit	200

In Table 1 the power consumption for the Litecoms Cart is determined from the Ball (now BAE Systems) specification sheet and calculating the power for a 6 receive panel/6 transmit panel configuration from the power consumption for a single panel. Note that the power consumption calculated for the Litecoms Cart includes the phased array only and does not account for the modem or any cooling systems.

V. CONCLUSION

Kymeta has commercialized a diffractive metasurface beamforming antenna for multi-orbit satellite communications. The power consumption for the antenna and total system power for the satcom terminal are the lowest amongst other electronically scanned antenna multi-orbit satcom terminals with similar capability. Future connectivity demands for the connected car and other ubiquitous computing use cases will demand connectivity to satellite networks across multiple orbits but will also require minimum power consumption. Diffractive metasurface technology presents that best approach to deliver the required connectivity at the lowest possible power consumption.

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