LEAKY-WAVE ANTENNAS FOR BEAM STEERING IN CUBESAT APPLICATIONS

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***Abstract* – Leaky-wave antennas (LWAs) present an attractive solution for CubeSat platforms by enabling low-profile, frequency-scanned beam steering without the complexity of conventional phased arrays. By exploiting controlled leakage of guided waves through periodic or tapered structures, LWAs inherently achieve directional radiation, offering lightweight, easily fabricated designs compatible with CubeSat constraints in volume, mass, and power. This paper reviews the fundamental principles governing LWA operation, including dispersion characteristics and beam scanning behavior, with emphasis on how structural modulation affects radiation patterns, scan range, and beamwidth. The discussion includes printed and substrate-integrated implementations, such as composite right/left-handed (CRLH) structures and metasurface-inspired designs. Additionally, electronically reconfigurable LWAs using varactors, MEMS, or liquid crystals are examined for dynamic beam control. Applications in Earth observation, inter-satellite links, and telemetry, tracking, and control (TT&C) are outlined, positioning LWAs as efficient and compact alternatives to traditional steerable arrays for next-generation CubeSat missions.**

I. INTRODUCTION

The proliferation of CubeSat missions has transformed space systems engineering, enabling unprecedented access to space through standardized, cost-effective platforms. CubeSats now serve critical roles in Earth observation, telecommunications, and scientific research. However, the stringent size, weight, and power (SWaP) constraints inherent to CubeSat platforms, typically conforming to 10 cm × 10 cm × 10 cm unit (1U) multiples, impose significant challenges on antenna subsystem design. Communication antennas must deliver adequate gain and directivity while occupying minimal volume, consuming low power, and maintaining compatibility with launch vehicle deployment mechanisms [1].

Traditional beam-steering solutions face substantial difficulties in the CubeSat context. Mechanically steered antennas introduce moving parts that compromise reliability and require dedicated actuation power [2]. Conventional phased arrays demand complex feed networks, numerous phase shifters, and substantial DC power, representing a significant fraction of typical CubeSat power budgets [3].

Leaky-wave antennas (LWAs) offer a compelling alternative. By exploiting controlled leakage of electromagnetic energy from a guided-wave structure, LWAs achieve directional radiation without requiring complex feed networks or numerous active elements [4]. The fundamental mechanism, progressive phase variation along the antenna aperture, inherently produces a directive beam whose pointing angle varies with frequency. This frequency-scanning capability enables beam steering through simple frequency selection rather than phase shifter arrays, dramatically reducing system complexity and power consumption [5].

This paper presents a comprehensive survey of leaky-wave antenna technologies with specific emphasis on their applicability to CubeSat missions. Section II establishes the theoretical foundations of LWA operation. Section III examines various LWA topologies suitable for CubeSat implementation. Section IV explores reconfigurable LWA designs. Section V discusses specific CubeSat mission applications and concludes with future research directions.

II. FUNDAMENTALS OF LEAKY-WAVE ANTENNAS

Leaky-wave antennas represent a class of traveling-wave radiators in which electromagnetic energy propagates along a guiding structure while continuously leaking into free space [6]. The fundamental operating principle of LWAs enables the structure to function simultaneously as both a transmission line and a radiating aperture. The electromagnetic wave propagating along the antenna experiences a complex propagation constant characterized by both an attenuation component and a phase component. In conventional transmission lines, attenuation arises primarily from conductor and dielectric losses. However, in leaky-wave structures, the attenuation includes an additional radiative component that represents the desired power leakage into free space. Effective LWA design maximizes this radiative attenuation relative to ohmic losses to achieve high radiation efficiency. The radiation mechanism fundamentally relies on phase matching between the guided wave and free-space radiation modes. When the phase constant of the guided wave matches the projection of the free-space wavenumber at a particular angle, constructive interference occurs, and radiation is directed at that angle from the antenna normal. This phase-matching condition directly connects the guided-wave propagation characteristics to the radiation angle, forming the physical basis for frequency-controlled beam steering in LWAs. As the operating frequency changes, the guided-wave phase constant varies according to the structure's dispersion characteristics, causing the radiation angle to sweep through space [7], [8]. Fig. 1 illustrates the fundamental leaky-wave radiation mechanism.

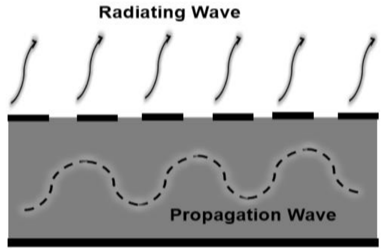


Fig. 1. LWA leakage mechanism.

The dispersion relation fundamentally determines LWA radiation characteristics and beam-steering behavior. The radiation angle of a leaky-wave antenna is governed by the phase-matching condition between the guided wave and free-space radiation. This relationship can be expressed as [7]:

$$cos\theta_0 = \frac{\beta_n}{k_0} \qquad (1)$$

where where θ_0 is the main beam direction measured from the antenna normal, β_n is the phase constant of the nth spatial harmonic of the guided wave, and $k_0 = 2\pi/\lambda_0$ is the free-space wavenumber. This equation demonstrates that the beam direction is directly determined by the normalized phase constant. For typical structures exhibiting normal dispersion, increasing frequency causes β_n to increase, thereby changing the beam angle. When $\beta_n/k_0 < 1$, the structure supports fast-wave radiation capable of coupling to free space. Values $\beta_n/k_0 > 1$ indicate a slow wave that cannot radiate directly without additional phase-matching mechanisms such as periodic loading [9].

The beamwidth of a leaky-wave antenna, which determines its angular resolution and directivity, depends on both the antenna's physical length and the radiation angle. The half-power beamwidth can be approximated as [7]:

$$\Delta\theta = \frac{\lambda_0}{L_r\, sin\theta_0} \qquad (2)$$

where $\Delta\theta$ is the half-power beamwidth, λ_0 is the free-space wavelength, L_r is the radiating length of the antenna (the effective length over which radiation occurs), and θ_0 is the main beam direction. This expression reveals several important design insights for CubeSat applications. First, longer antennas produce narrower beams, providing higher directivity and gain, critical for link budget improvements in power-constrained platforms. Second, the beamwidth varies with scan angle, becoming broader at angles closer to endfire (θ_0 approaching 90°) and narrower near broadside. For CubeSat implementations where panel length is limited (typically <30 cm for a 3U face), achieving narrow beamwidths at high frequencies is feasible, enabling high-gain directional communication [10].

The radiation efficiency and overall antenna performance depend on the normalized leakage constant, which determines how rapidly energy escapes the guiding structure. Optimal performance typically occurs when approximately 80-90% of input power radiates before reaching the load. If leakage is too weak, insufficient power radiates, and most energy reaches the terminal load, reducing efficiency. Conversely, excessive leakage causes power to radiate predominantly from the antenna's input region, producing a short effective radiating length L_r and consequently a broad beam with reduced gain according to equation (2) [7], [11].

Several factors specific to CubeSat environments influence LWA design. First, the limited available antenna length due to the CubeSat face constraints limits the achievable gain and beamwidth. Second, operating frequency must balance link budget requirements against atmospheric effects and spectrum allocations. Third, the antenna must maintain performance across thermal cycling and survive launch vibration. The frequency-scanning characteristic introduces fundamental coupling between operating frequency and beam direction, which must be carefully managed in communication link design [1 - 3].

III. LWA TOPOLOGIES FOR CUBESAT INTEGRATION

A. *Printed Leaky-Wave Antennas*

Printed LWAs implemented on standard PCB substrates offer the lowest profile and simplest fabrication pathway for CubeSat integration [12]. One of the simplest approaches involves using a uniform microstrip line with periodically spaced slots, stubs, or patches that disturb the guided mode and promote radiation. The period p must satisfy $p < \lambda g$ (the guided wavelength) to avoid grating lobes. These structures can be implemented on thin substrates with standard materials. Advantages include minimal thickness, ease of integration with other RF circuitry, and compatibility with deployable panels.

Recent advancements in compact planar LWA design further demonstrate the potential of these structures for wide-band, directive broadside radiation. For example, a low-cost, compact LWA based on an annular metallic strip grating (MSG) on a dual-layer grounded dielectric substrate has been shown to form a parallel-plate open waveguide and support broadside pencil-beam patterns over a wide frequency range (21.9–23.9 GHz) with more than 8.5% bandwidth [13]. The MSG configuration of the LWA is shown in Fig. 2.

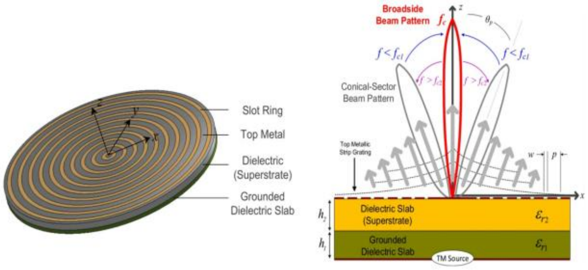


Fig. 2. MSG-based LWA configuration [13].

B. *Substrate Integrated Waveguide LWAs*

Substrate integrated waveguide (SIW) technology synthesizes rectangular waveguide behavior using rows of metalized vias within a dielectric substrate. SIW-based LWAs combine low-loss, high-power-handling characteristics with planar fabrication advantages. The most common configuration features a linear array of slots machined into the top conductor along the waveguide's longitudinal axis [14].

Recent research highlights the potential of SIW-based LWAs for CubeSat communication, offering circular polarization, broadband operation, and high gain in a compact form factor. For instance, a novel planar SIW LWA utilizing periodic fan-shaped slots achieves efficient circularly polarized radiation with beam steering capabilities and polarization flexibility over a wide frequency band. When two such LWAs are integrated on perpendicular faces of a 1U CubeSat to form a conformal array, the total gain and directivity are further enhanced while maintaining a low profile and lightweight structure. This approach addresses key requirements for CubeSat missions, including dual circular polarization, wide bandwidth, and high directivity [15].

C. *Composite Right/Left-Handed (CRLH) Structures*

Composite right/left-handed (CRLH) metamaterial transmission lines have transformed LWA design by enabling continuous beam scanning through broadside. CRLH lines achieve their unique dispersion characteristics by combining series capacitance and shunt inductance (left-handed elements) with the natural series inductance and shunt capacitance (right-handed elements) of conventional transmission lines [16]. This duality allows for functionalities such as full-space dynamic beam scanning, multi-band operation, and the realization of pencil, fan, or conical beams without complex feed networks.

Practical CRLH-LWAs are typically implemented using unit cells composed of series interdigital capacitors and shunt inductive stubs. For a balanced CRLH configuration, the dispersion relation can be accurately expressed and analyzed using full-wave modal approaches, which eliminate open-stopband effects and ensure nearly constant radiation efficiency across the scanning range, including broadside [17]. The presence of both series and shunt radiating elements within the unit cell architecture is essential for achieving efficient broadside radiation.

D. *Metasurface-Inspired Designs*

Recent advances in metasurface technology have inspired a new generation of LWAs with unprecedented control over radiation characteristics. By spatially varying the surface reactance along a guiding structure, designers can control both the leakage rate and aperture phase distribution independently. This capability enables highly tailored radiation patterns, including pencil beams, shaped beams, and multi-beam configurations from a single feed [18]. In addition to advanced beamforming, recent developments have demonstrated that metasurface-inspired LWAs can also achieve dual-band operation and efficient broadside radiation in compact formats suitable for CubeSats. For example, a substrate-integrated waveguide (SIW) LWA featuring middle-point feeding and lateral shorting walls enables broadside radiation at two distinct K-band frequencies, with realized gains up to 8 dBi and efficiencies approaching 87%. This dual-frequency capability can support flexible uplink and downlink operations, while the low-profile antenna design is compatible with placement beneath CubeSat solar panels, maximizing available surface area for power harvesting. Such innovations further broaden the versatility and application potential of LWAs in small satellite communications [19].

IV. RECONFIGURABLE LWAs FOR DYNAMIC BEAM CONTROL

While frequency scanning provides inherent beam steering in conventional leaky-wave antennas, many CubeSat missions increasingly demand more versatile control capabilities. These include independent beam steering at fixed frequencies, adaptive pattern shaping to respond to changing mission requirements or link conditions, and polarization switching for improved signal robustness. Such dynamic reconfigurability is essential for optimizing communication performance and meeting the evolving needs of small satellite applications.

A. Varactor-Based Tuning

By incorporating varactors in series or shunt configurations, the structure's effective permittivity and propagation constant (β) can be continuously tuned, enabling dynamic beam steering at a fixed operating frequency. This approach allows for real-time adjustment of the antenna's main beam direction without changing the signal frequency. For instance, recent work has demonstrated a varactor-tuned leaky-wave antenna based on a coplanar waveguide-grounded (CPWG) composite right/left-handed (CRLH) transmission line, where the application of DC voltage to the varactors directly controls the phase constant of the fundamental mode. The resulting LWA achieves wide-angle scanning from −66° to 62° at 3.0 GHz, maintains a peak gain of 9.9 dBi with less than 4.9 dB gain fluctuation, and operates with radiation efficiency exceeding 50% across a 13% bandwidth. The design is notable for its simple structure, low cost, and experimental validation with a fabricated prototype [20]. The structure and layout of the varactor-tuned leaky-wave antenna are illustrated in Fig. 3. As shown, the antenna consists of a coplanar waveguide-grounded (CPWG) transmission line loaded with varactors, with the top view of a single unit cell also depicted for clarity [20].

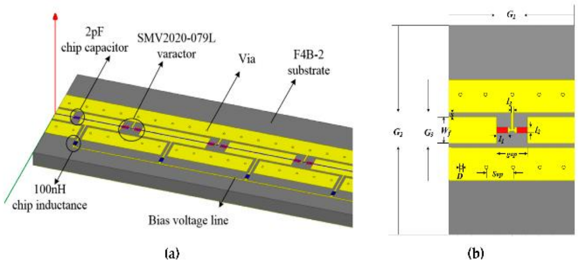
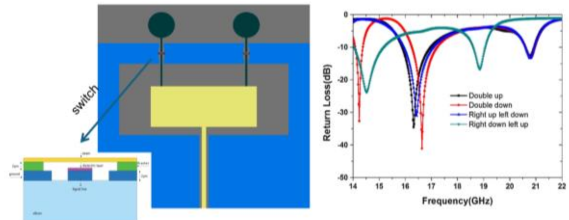


Fig. 3. Scheme of the varactor-tuned LWA: (a) overall structure; (b) top view of the unit cell [20].

B. MEMS Switches

Micro-electromechanical systems (MEMS) switches have emerged as effective tuning elements for reconfigurable LWAs, offering a valuable trade-off between tuning range, loss, and integration complexity. While electronic beam steering in LWAs can be achieved using a variety of active elements, such as semiconductor switches, PiN diodes, liquid crystals, and ferrites, MEMS switches are particularly attractive due to their low insertion loss and broad capacitance tuning range, often surpassing that of varactor diodes [7], [21]. MEMS-based reconfiguration typically operates by mechanically adjusting the air gap within a capacitor structure, enabling precise control of the antenna's propagation characteristics and, consequently, its beam direction. Such devices, when integrated onto coplanar waveguide-grounded (CPWG) platforms, have demonstrated tunable capacitance in the picofarad range and are suitable for frequencies up to 50 GHz [22].

Fig. 4 shows the structure of a frequency-tunable antenna controlled by MEMS switches. The figure includes the antenna layout, the MEMS switch diagram, and the return loss curves for different switch configurations. When both switches are set to "up," both to "down," or with the right switch "up" and left switch "down," the antenna exhibits a resonance at 21 GHz. However, with the right switch "down" and left switch "up," this resonance does not occur [23].



(a) (b)

Fig. 4. (a) Antenna structure and MEMS switch diagram; (b) simulated return loss for different switch states [23].

Although MEMS switches generally require higher bias voltages and are physically bulkier than semiconductor switches, they benefit from high linearity, low power consumption, and the ability to provide nearly continuous tuning within their mechanical limits. However, their tuning range is typically smaller and discontinuous compared to other tuning means, and their switching speed is moderate. Despite these limitations, MEMS-based LWAs are well-suited for CubeSat applications, where low loss, high-frequency operation, and reconfigurability are critical. Recent studies have shown that MEMS technology enables reliable, wide-angle electronic beam scanning in microstrip and SIW-based LWAs, thus supporting dynamic link adaptation and robust satellite communications in variable environments.

C. Liquid Crystal Integration

Liquid crystal (LC) materials have emerged as promising candidates for passive, electrically tunable beam-steering in LWAs, offering a unique combination of low loss, broad tunability, and suitability for microwave and millimeter-wave applications. By applying a bias voltage, the dielectric properties of LCs can be precisely controlled, enabling dynamic adjustment of the phase constant and, consequently, the main beam direction without requiring moving parts [24], [25]. Recent developments include LC-based phase shifters with large, continuous tuning ranges and high figure-of-merit, as well as LC-tunable reflectarray antennas capable of continuous beam scanning over ±25° at millimeter-wave frequencies using low bias voltages [25]. These devices demonstrate not only efficient beam steering but also radiation hardness, suggesting their viability for space environments such as CubeSat missions.

Advances in LC-LWA integration have led to the realization of compact, dual-band, and wide-angle scanning antennas, with some designs employing dispersion sensitivity enhancement (DSE) components to extend the beam scanning range by over 56% while maintaining impedance matching and balanced conditions [25]. Nematic LC-based LWAs have demonstrated up to 32° electronic beam scanning at 12 GHz with stable gain and good impedance characteristics, further highlighting the flexibility of LC technology [26]. The compatibility of LC-based tuning with standard PCB and ceramic fabrication methods, along with their mechanical stability, positions liquid crystals as a highly attractive solution for reconfigurable, low-profile antennas in next-generation CubeSat and satellite communications systems.

V. CONCLUSION AND FUTURE DIRECTIONS

Leaky-wave antennas represent a compelling solution for CubeSat communication systems, offering directive, steerable radiation from low-profile structures compatible with severe size, weight, and power constraints. This survey has examined theoretical foundations, topology options from printed designs to metamaterial structures, and reconfiguration techniques for next-generation small satellite platforms.

Printed microstrip LWAs offer simplicity and high flight heritage, while SIW implementations provide superior shielding and mechanical robustness. CRLH structures uniquely enable efficient broadside radiation and wide-angle scanning, and metasurface designs offer unprecedented flexibility in wave manipulation and beam shaping. Electronic reconfiguration using varactors, MEMS, or liquid crystals adds dynamic beam control but introduces complexity and modest power consumption. The value proposition depends on mission requirements: static missions may not justify reconfigurable implementations, while dynamic missions benefit substantially from adaptive beam control.

LWAs offer significant advantages across CubeSat missions. For Earth observation, LWAs could improve synthetic aperture radar resolution through their lightweight, low-profile design, enabling larger apertures within constrained mass budgets. For inter-satellite links, LWAs provide advantages due to significantly lower power consumption compared to phased array antennas, while enabling spatial frequency reuse with substantial interference reduction. In telemetry, tracking, and control applications, LWAs achieve higher gain and wider scan range compared to conventional patch antennas.

Promising research directions include: dual-polarization LWAs for polarization diversity and frequency reuse; multi-beam configurations for multi-user communications; millimeter-wave implementations for high data rates; AI-optimized design methodologies achieving significantly faster design cycles; integrated RF front-ends for mass reduction; and deployable architectures achieving higher gain while folding to compact stowed volumes.

The convergence of maturing LWA technology with expanding CubeSat capabilities positions these antennas as key enablers for next-generation small satellite systems. As CubeSats evolve toward operational missions, leaky-wave antennas, with their favorable mass-to-performance ratios and design flexibility, stand ready to meet growing demands for compact, efficient, steerable antennas. Continued research addressing reconfigurability, millimeter-wave implementations, and system integration will accelerate the transition from laboratory demonstrations to operational flight systems in the small satellite community.

VI. ACKNOWLEDGMENT

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