Software-defined Reconfigurable Antenna Using Slotted Substrate Integrated Waveguide for Ka-band Satellite-on-the-Move Communication

Yifan Wang. A.M. Abbosh

School of ITEE, University of Queensland, Brisbane, QLD4072, Australia
yifan.wang@uq.edu.au

Abstract— **A software-defined pattern reconfigurable Ka-band antenna for high-speed satellite-on-the-move (SOTM) application is presented. The proposed antenna employs the concept of travelling-wave slotted integrated waveguide to achieve a high-directivity radiation beam as needed for satellite communications. The substrate integrated waveguide (SIW) is employed as the antenna's main structure to lower the antenna's cost and weight. To realize the radiation-pattern configurability at a certain frequency, hundreds of computer-controlled PIN diodes are installed on the top slotted layer of the SIW structure to control the effective distance between the slots. The design parameters of the antenna are calculated using the leaky-wave space harmonic theory and further verified by full-wave simulations. As a proof of concept, a linear array with total length of 20 cm×1 cm is designed and simulated. Up to $\pm 20°$ steering range of the main beam can be achieved with 15 dBi gain. In a planar structure of dimensions 20 cm×20 cm, the gain is increased to 22 dBi gain at 20 GHz.**

Keywords— *Reconfigurable antenna; satellite on the move; substrate integrated waveguide; travelling wave; leaky wave antenna*

I. INTRODUCTION

Ka-band Satellite-on-the-move (SOTM) communication terminal is an antenna subsystem that can be placed on mobile platforms, such as vehicles, airplanes, ships or unmanned aerial vehicles, to provide a continuous broadband wireless link to low-orbit or geostationary satellites. To date, most of the Ka-band SOTM terminals, such as [1-2], are driven by mechanical automation subsystems, which are not suitable for aerodynamic platform utilization due to their heavy-weight and bulk structure.

To be more compatible with aerodynamic requirements, the recent low-profile terminals developed using electronic-controlled compact structure, such as [3-4], can achieve beam steering without rotating the antenna body. However, such fixed terminals cannot achieve a 2D versatile beamforming with small pointing error and agile system response; moreover, their high manufacturing costs make them inaccessible for most middle or low-end markets. Due to the technical challenges of manufacturing compact active array structures at Ka-band with beam-forming capability, there is no product, to date, to our knowledge, to fill the gap of the important Ka-band SOTM terminal market.

This paper presents a software-defined SOTM terminal that possess a complete planar travelling-wave structure with radiation-pattern reconfigurable capability. The antenna is realized using a substrate integrated waveguide (SIW) structure embedded with hundreds of computer-controlled PIN switches to tune the surface-wave space harmonic profile for beam steering purpose. Since all the radiation elements on the proposed antenna are passively-fed, and the utilized PIN diodes are of extremely low cost, the total cost of the proposed antenna system is anticipated to be significantly low.

II. SUBSTRATE INTEGRATED TRAVELLING-WAVE SLOTTED WAVEGUIDE ARRAY MODELLING

Slotted waveguide arrays, as illustrated in Fig. 1a, are typically used over a wide range of microwave frequencies and particularly popular for applications requiring fan- and pencil-beam radiation. Linear slot arrays that are aligned along a single waveguide can produce fan beams. Thus, a sharp pencil beam can be realized by arraying a number of linear arrays together to form a planar array as shown on Fig. 1b.

The linear waveguide array generally falls into one of two fundamental categories, namely the resonance and travelling-wave types [5]. In the resonance type, there is an identical phase of radiation from each slot, and thus the broadside fan-shaped radiation beam is not adjustable. In the travelling-wave type, the magnitude of the wave launched from the slots decays towards the load as the energy coupled out and radiated sequentially by the slots. The space-harmonic theory [5] on electromagnetic propagation suggests that, by allocating a proper space between the slots, a progressive phase shifting of radiation can be generated between adjacent slots. Therefore, the phased slot array generated by this approach results in a fan-beam radiation that squints off broadside to both forward and backward direction as shown in Fig. 1a and scans with center frequency (f_0) or slot periodicity (p_{slot}). In the first-order space harmonic condition ($n = -1$), the following equation describes the relationship between maximum radiation angle (θ_m), slot periodicity and operating frequency [5].
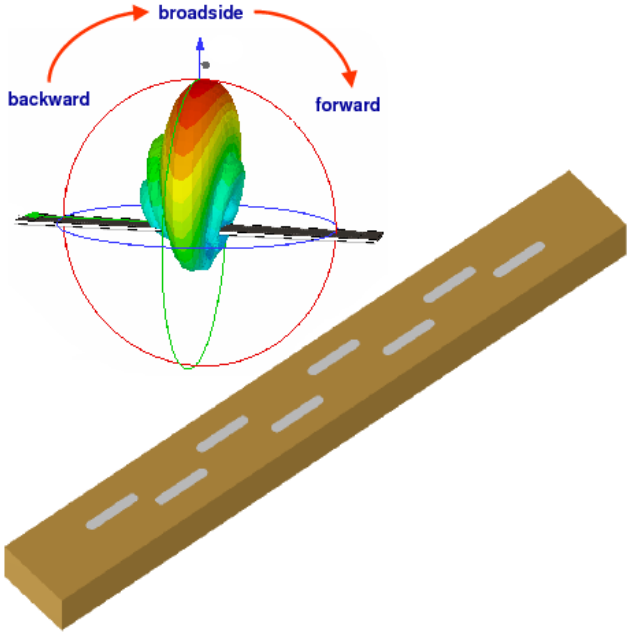
(a)

(b)

Fig.1 Slotted waveguide array on (a) standard rectangular waveguide (b) planar structure with SIWs.

$$\sin \theta_m = \frac{\lambda_0}{\lambda_g} + \frac{2n\lambda_o}{p_{slot}} = \frac{\lambda_0}{\lambda_g} - \frac{2\lambda_o}{p_{slot}} \qquad (1)$$

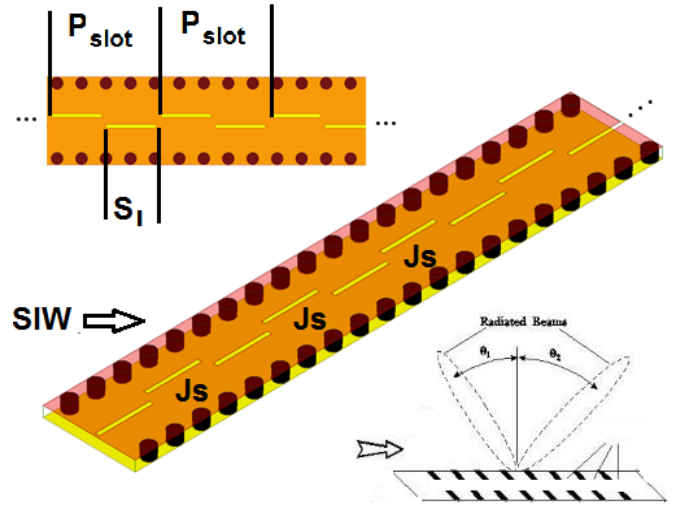where, λ_g is the SIW-guided wavelength, $\lambda_0 = c/f_0$ is the wavelength in free space.

Fig.2 Linear waveguide slot arrays on substrate integrated waveguide (SIW) and its adjustable fan-beam radiation pattern

As shown in Fig. 2, the substrate integrated waveguide (SIW) is used in this work to support TE_{10} mode propagation at the Ka band. Rogers 3003 with 1.905 mm thickness and relative dielectric constant of 3 is used as the substrate for the SIW. The dimensions of SIW are determined according to the guidelines from [6]. The length of the slot is designed as $S_l \approx \lambda_g/2$, and width $S_w \ll S_l$ to perturb the surface current $\vec{J_s}$ on the top conductive layer. Considering that the proposed SOTM terminal for the down link operates at the fixed frequency (20 GHz), the beam steering function can only be realized by tuning the slot periodicity (p_{slot}) on SIW. The theoretical calculation and our full-wave simulations suggest that, to provide $-20° < \theta_m < +20°$ steering range of the main beam, p_{slot} needs to be tuned between 13 mm and 17 mm.

III. SOFTWARE-DEFINED RECONFIGURABLE ANTENNA

To realize an adjustable slot periodicity with highest possible resolution, a software-defined slotted SIW realized by computer-controlled PIN diodes, as switches, is used as shown in Fig. 3. In this design, N=300 PIN diodes are utilized along each linear SIW structure with total effective radiation aperture of $L = 150\ mm$. The dimensions of the selected diodes are around $0.5\ mm \times 0.5\ mm$, and adjacent diodes are spaced at $Ds = 1\ mm$ distance. The operating status of those diodes can be controlled remotely by a matrix $[D]$ generated using a suitable algorithm in a computer. If the elements on each column represent the diode index, as shown in Fig. 3, the elements on each row represent M various profile of diodes status corresponding to M fan-beam radiations with different steering angles.

$$[D] = \begin{pmatrix} s_{11} & \cdots & s_{1N} \\ \vdots & \ddots & \vdots \\ s_{M1} & \cdots & s_{MN} \end{pmatrix}; s_{ij} = 0\ (off), s_{ij} = 1\ (on) \quad (2)$$

By switching off (high resistant, $s_{ij} = 0$) or switching on (high conductance, $s_{ij} = 1$) the diodes distributed along any two

pre-reserved slot on the SIW, the surface current $\vec{J_s}$ will be perturbed by the high-resistant-boundary condition and unperturbed by the high-conductance boundary condition. Thus, a proper allocation of the diodes status in terms of (1) results in a reconfigurable beam steering function. Fig. 4 illustrates the full-wave radiation pattern of the proposed software-defined structure. It shows that up to $\pm 20°$ steering range of the main beam can be achieved with 15 dBi gain from a linear array with total length of 20 cm×1 cm and more than 22 dBi gain from a planar array of dimensions 20 cm×20 cm at 20 GHz.
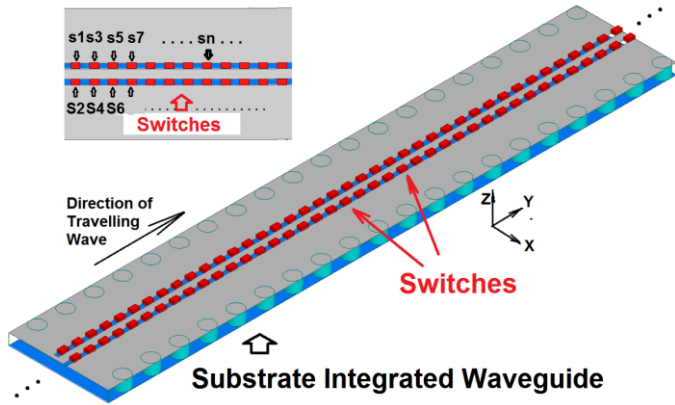

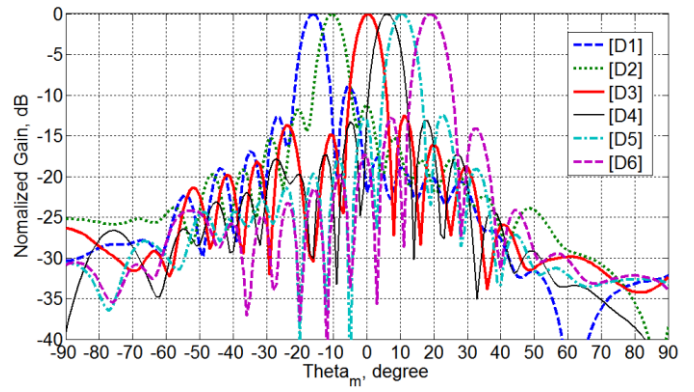Fig.3 Software-defined reconfigurable antenna structure on SIW.

Fig.4 Radiation pattern of the software-defined reconfigurable slotted SIW array on H-plane ($\varphi = 90°$).

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