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Study on the Effect of Different Feeding Structures on the Performance of Graphene Strips Reconfigurable LWA

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Abstract

This paper introduces a comparative study on the effect of using different feeding structures on the radiation characteristics of graphene strips leaky wave antenna (GS-LWA) at 2 THz. The effect of different plane wave launchers on the radiation characteristics of GS-LWA is investigated. A planar substrate integrated waveguide (SIW) horn antenna is investigated. It provides a peak gain of 18.2 dBi with a bandwidth of 21.95% and a SLL of 10.6 dB. End-fire radiation from parabolic reflector is employed to launch plane-wave in the GS-LWA. A matching BW of 0.82 THz is achieved with peak gain of 18 dBi. A coplanar fed Yagi-Uda like structure element is studied using a single element and two elements array. The two elements provided the highest matching of -40 dB over BW of 6% and gain of 16.5 dBi. Finally, tapered microstrip line is investigated, it introduces the lowest SLL − 16.1 dB with a gain of 17.5 dBi and BW of 39.57% (1.5–2.24 THz). The selection of proper feeding structure depends on the matching BW, peak radiated gain, and the lowest SLL. A full analysis of the GS-LWA from different feeding methods is presented.

Keywords Leaky-wave antenna · Frequency scanning · Graphene · Feeding mechanism

1 Introduction

Modern communication systems require creative antenna solutions to compete with low-profile circuit configurations for efficient performance [1]. A good antenna structure with an appropriate feeding mechanism plays a major part in the overall efficiency of communication systems. Antenna radiation characteristics are affected by the feeding structure which should be compact, low cost, and introduce good impedance matching bandwidth. Conventional feeding techniques for planar structures have induced undesirable surface wave

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excitation (SW) which results in high power loss [2]. Leaky-wave antennas (LWAs) are planar antenna with low-profile and ease of fabrication. It is suitable for a variety of applications including satellite systems, future 5G communication devices and wireless power transmission systems [3]. LWAs are travelling-wave antennas that characterized by a beam-scanning ability, narrow bandwidth, low price, high gain and high efficiency by using simple feeding mechanisms [4]. It provides a solution for most wireless communication systems that operate in a pre-defined frequency band with a specified beam scan [5]. The LWA have different structures, such as periodic slots, periodic metal bands, dielectric array at the top of the guide and sinusoidal modulated surface impedances [6–8]. LWA's applications require a wide range of frequency sweep to get a desired range of beam scanning directions. The complex propagation constant of LWAs is modified to produce the required scanning beam and hence reconfigurable LWAs operation [9]. Reconfigurable LWAs are designed using different electronic techniques such as PIN diodes, photosensitive switches, varactor diodes, or varying the surface impedance [10, 11]. Reconfigurable LWAs using the graphene material are designed and investigated for THz applications [12, 13]. Different feeding structures are investigated such as, coplanar waveguide (CPW) -fed slot launcher, metallic grating lenses were investigated to lunch plane waves. A probe-fed dual-offset Gregorian reflector system is designed to excite quasi-TEM wave inside a parallel-plate waveguide [14–16]. Slot Yagi-Uda antenna launcher is one of the suitable sources for TM0 mode surface wave. Rectangular waveguides and flare horns are widely used [17], and for wide bandwidth application ridged structures are used [16]. Flared slot antenna produced a stable radiation beam near the end-fire direction has been introduced in [18]. Linear (1D) and planar (2D) LWAs based on reconfigurable materials such as graphene and plasma have been investigated and analyzed for beam-scanning applications as discussed in [19–21].

In this paper, a graphene band leakage wave antenna design is designed and tested in the 1.56 THz to 2.2 THz frequency band. Different feeding techniques and their effect on the GS-LWA radiation characteristics are studied. A comparison between employing SIW horn, parabolic reflector, Yagi-Uda launchers, and tapered microstrip line is introduced. The finite integral technique (FIT) is used to design and analyze the radiation characteristics of the proposed LWAs configurations.

2 Design of a GS-LWA

Figure 1 illustrates the configuration of the GS-LWA designed to support 2 THz wireless communications. It consists of graphene strips with periodicity, P=8, printed on h=35 μm thick SiO_2 dielectric substrate with ϵ_r =3.9. The graphene strips have width, $S = 7.36\mu m$ and are separated by a gap of width$G = 2\mu m$. The surface conductivity of graphene strips is modeled using Durde model given by [22]:

$$Z_s\left(\omega,\,\mu_c,\,\Gamma,\,T\right) = \frac{1}{\left(\sigma_{inter}\left(\omega,\,\mu_c,\,\Gamma,\,T\right) + \sigma_{intra}\left(\omega,\,\mu_c,\,\Gamma,\,T\right)\right)} \tag{1}$$

where:

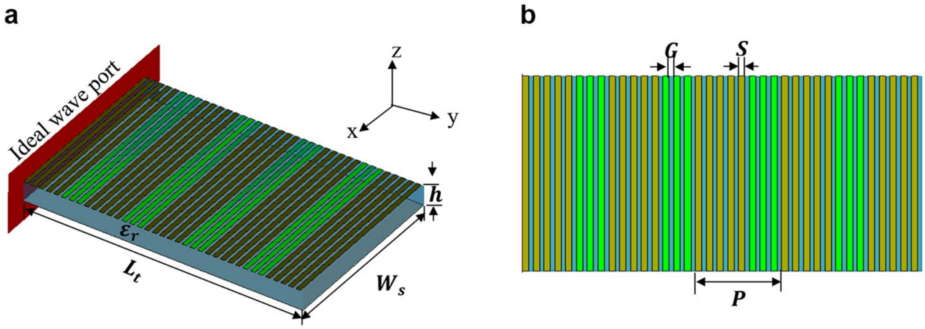

Fig. 1 The geometry of GS-LWA fed by ideal wave port. (**a**) 3D view (**b**) Top view

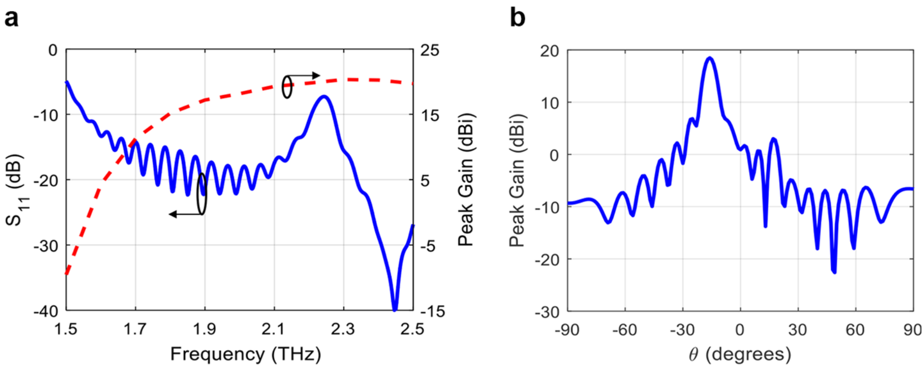

Fig. 2 (**a**) The S11 and peak gain versus frequency, (**b**) The gain pattern versus angle at 2 THz for the GS-LWA fed by ideal wave port in y-z plane

$$\sigma_{intra}(\omega,\ \mu_c,\ \Gamma,\ T) = -j\frac{e^2 k_B T}{\pi\hbar^2(\omega - j2\Gamma)}\left(\frac{\mu_c}{k_B T} + 2\ln\left(e^{-\frac{\mu_c}{k_B T}} + 1\right)\right) \tag{2}$$

$$\sigma_{inter}(\omega,\ \mu_c,\ \Gamma,\ T) = -j\frac{e^2}{4\pi\hbar}\ln\left(\frac{2|\mu_c| - (\omega - j2\Gamma)\hbar}{2|\mu_c| + (\omega - j2\Gamma)\hbar}\right) \tag{3}$$

ω is the operating angular frequency, Γ is the scattering rate, T is the temperature, k_B is the Boltzmann's constant and $\hbar$ is the reduced Planck's constant. The graphene surface impedance is controlled by the chemical potential, μ_c, which depends on the free carrier density. It is electrically controlled via the application of DC voltage. The GS-LWA unit includes five-biased graphene strips (ON-state with $\mu_c = 1eV$) and three-unbiased graphene strips (OFF-state with $\mu_c = 0$) constructing code of μ_c =11,111,000. An ideal wave port is used to launch a plane-wave excitation of the GS-LWA with total dimensions $L_t \times W_s \times h = 1350 \times 300 \times 35$ μm^3. The frequency responses of S_{11} and peak gain are plotted in Fig. 2a. The GS-LWA introduces impedance bandwidth (BW) of 34% extended from 1.56 THz to at f =2.2 THz with peak gain of 18.5 dBi. The gain pattern versus angle at 2 THz is shown in Fig. 2b. The GS-LWA radiates a directed beam at θ=-16° direction with half-power beamwidth (HPBW) of 6.4 ° and side lobe level (SLL) of -11.6 dB. The E-field distribution on the GS-LWA at 1.9 THz, 2 THz, and 2.1 THz are plotted in Fig. 3. It is noticed that the plane wave is propagating along the GS-LWA structure at different frequencies. In the following sections different feeding structure is studied to launch plane waves excitation signal to the GS-LWA.

2.1 GS-LWA Fed by SIW H-Plane Planar (SIWH) Horn Antenna

The substrate integrated waveguide (SIW) technology is an efficient technique to produce planar, low profile and low price antennas. This technology enables an antenna to be more easily integrated with other system components on the same chip [23]. SIW-horn antenna consists of dielectric substrate coated from the top, and the bottom by metallic ground planes connected through two flared rows of metallic pins. The radius and separation of metallic pins are adjusted for negligible leakage energy. Different SIW-horn antennas are investigated and introduced in [24]. A planar H-plane horn antenna based on SIW technology is constructed to radiate end-fire waves at 2 THz. The geometry of the SIWH antenna loaded with the GS-LWA is plotted in Fig. 4. The SIWH-horn antenna consists of two metallic plates sandwiched by SiO_2 substrate$\epsilon_r = 3.9$. Two flared rows of metallic pins with radius R_p=5.8 μm and separation by S_p=14.5 μm are inserted to connect the upper and lower sheets of the horn antenna. A 50 Ω coaxial probe is located at L_f=21.75 μm from the shorted end to feed the horn. The optimized antenna dimensions at 2 THz are given by: L_1 =107.3 μm, L_2= 290.8 μm, L_f=27.55 μm, w_1=84 μm, and w_2=322 μm. A dielectric lens of $\epsilon_r = 3.9$with $L_m = 70$ μm is placed between the SIWH and GS-LWA to improve the impedance matching. Figure 5a shows the S_{11} and peak gain against frequency for the GS-LWA fed by SIWH antenna. Good impedance matching of 21.9% from 1.72 THz to 2.15 THz with peak gain of 18.2 dBi. The gain pattern versus angle at 2 THz is shown in Fig. 5b. The GS-LWA radiates a directive beam at θ=-16 ° with HPBW=6.4 °.

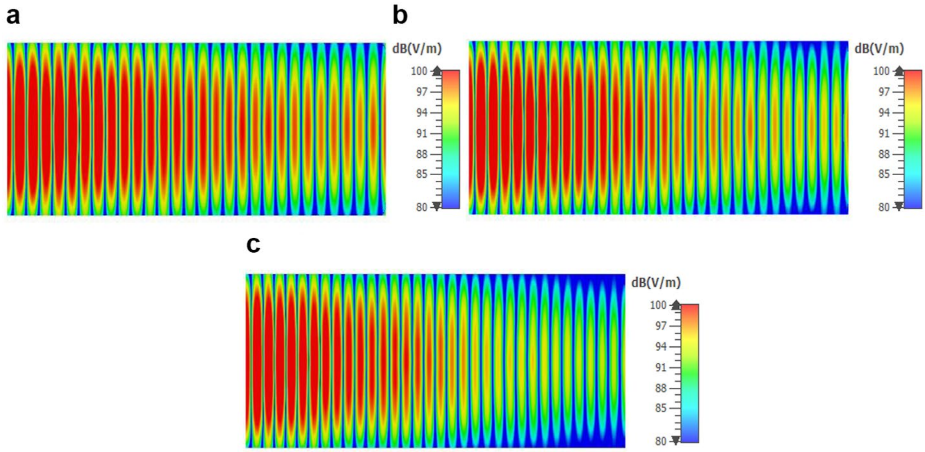

Fig. 3 The E- field distributions at different frequencies for the GS-LWA fed by an ideal wave port. (**a**) f=1.9 THz (**b**) f=2.0 THz (**c**) f=2.1 THz

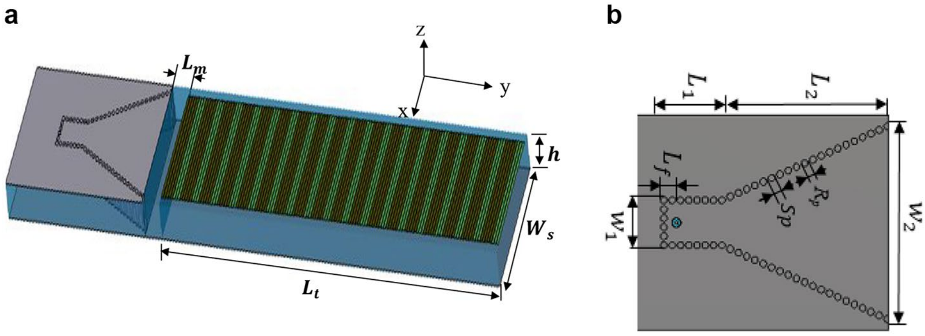

Fig. 4 The proposed structure of the SIWH - horn antenna loaded with GS-LWA. (**a**) The 3D array construction, (**b**) The SIW feeding horn antenna

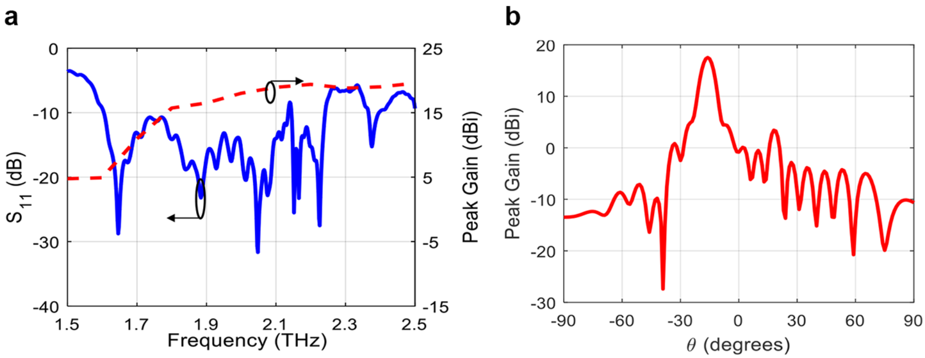

Fig. 5 (**a**) The S_{11} and peak gain versus frequency, (**b**) The gain pattern versus angle at 2 THz for the GS-LWA fed by the SIWH horn antenna at y-z plane

2.2 GS-LWA Fed by Parabolic Reflector

A unidirectional plane wave launcher reflecting parabolic structures with a compact profile is investigated. It should provide a broad bandwidth, minimized the phase differences and get a uniform electric field distribution at the waveguide aperture, to improve the launching efficiency. A quasi-plane wave is obtained at the aperture by modifying the parabolic reflecting wall, and probe-fed location. The parabolic reflecting structure introduces stable radiation pattern, improved gain, and high radiation efficiency [25–26]. The GS-LWA is fed using a unidirectional plane wave launcher with reflecting parabolic reflecting wall (following the equation $y^2 = 4cx$, where $c = 35\mu m$ is the focal length) as shown in Fig. 6. A50 Ω coaxial probe is extended through the substrate with height $h_f = 20\mu m$ at the focus of the parabolic reflector and $C_1 = 185\mu m$ to achieve wide matching impedance bandwidth. The coaxial probe excites cylindrical EMWs, where the backward wave is reflected by the parabolic reflector to produce plane wave. The S_{11} and peak gain against frequency of the GS-LWA fed by parabolic reflector are plotted in Fig. 7a. Wide impedance BW of 39.8% is achieved with peak gain of 18 dBi. A directive gain pattern at θ=-16° direction with HPBW of 6.4° and SLL of -11.6 dB is achieved at 2 THz as shown in Fig. 7b.

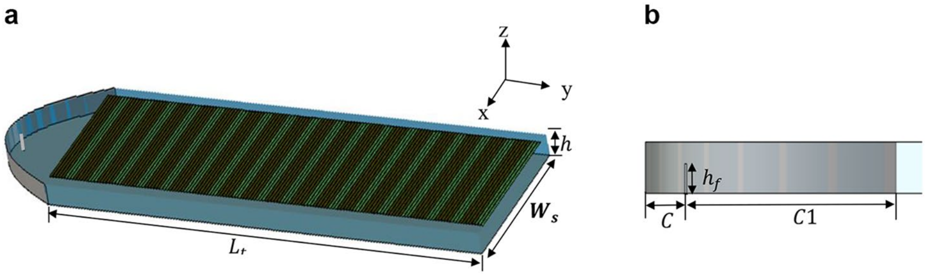

Fig. 6 Proposed structure of parabolic reflector antenna loaded with GS-LWA. (**a**) The 3D array structure, (**b**) The parabolic feeder

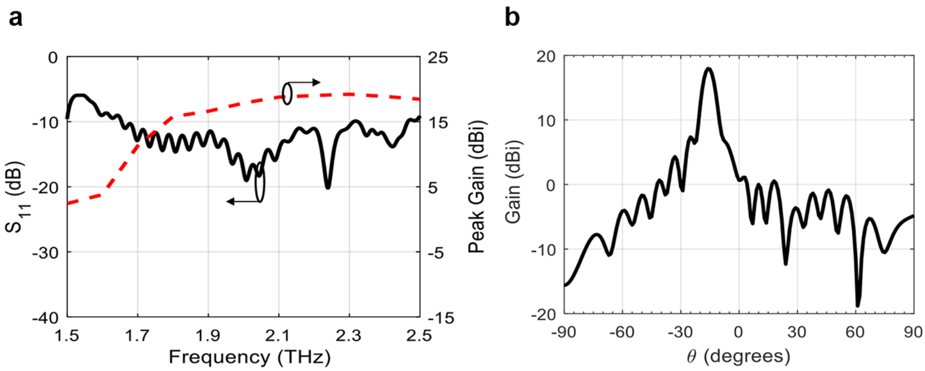

Fig. 7 (**a**) The S11 and peak gain versus frequency, (**b**) The gain pattern versus angle at 2 THz for the GS-LWA fed by parabolic reflector antenna at y-z plane

2.3 GS-LWA Fed by Yagi-Uda Like Antenna

Coplanar waveguide fed Yagi-Uda is a surface wave launcher that provides very narrow high-matched bandwidth. An array of two Yagi-Uda like elements is used to generate SW field pattern with high gain, wide matching bandwidth and efficient performance [27]. A coplanar waveguide fed Yagi-Uda like launcher is introduced to feed the GS-LWA as shown in Fig. 8. Single and double Yagi-Uda like launcher are investigated. Each launcher consists of two main parts as shown in Fig. 8c. The dipole part has width$x = 41.75\mu m$. The reflector part reduces the wasted power in the back lobe has dimensions $2t = 1.7\mu m$, $L_{y4} = 10.8\mu m$, L_{y5} = 12.8μm, and L_{y3} = 7.5μm, L_{y1} = 13.14μm, and L_{y2} = 10.24μm, *h nally a matching element a*. The S_{11} and peak gain against frequency for single and double Yagi-Uda like launchers are plotted in Fig. 9a. The matching BWs are 9.62% and 6.0% for single and double Yagi-Uda Like elements feeders. The peak gain is 15.1 dBi for the single Yagi-Uda like element and increased to 16.5 dBi for double Yagi-Uda like elements. Figure 8b shows the gain pattern versus angle at 2 THz. The SLL is -12.2 dB and −10.9 dB for single and double Yagi-Uda like elements, respectively.

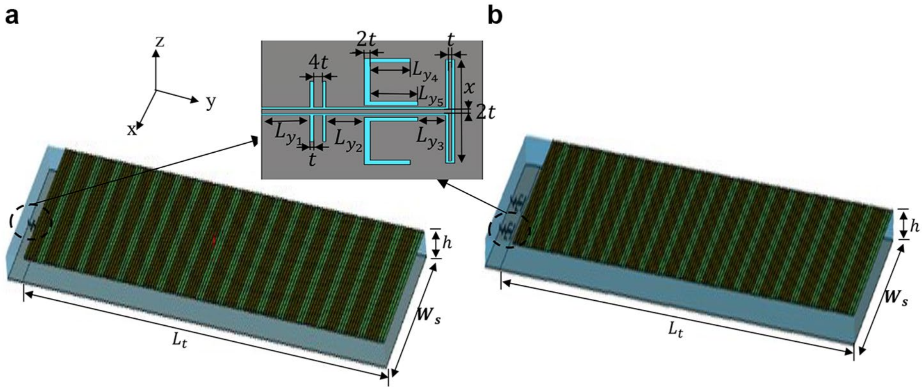

Fig. 8 The geometry of GS-LWA fed by, (**a**) Single, (**b**) Two Yagi-Uda like elements

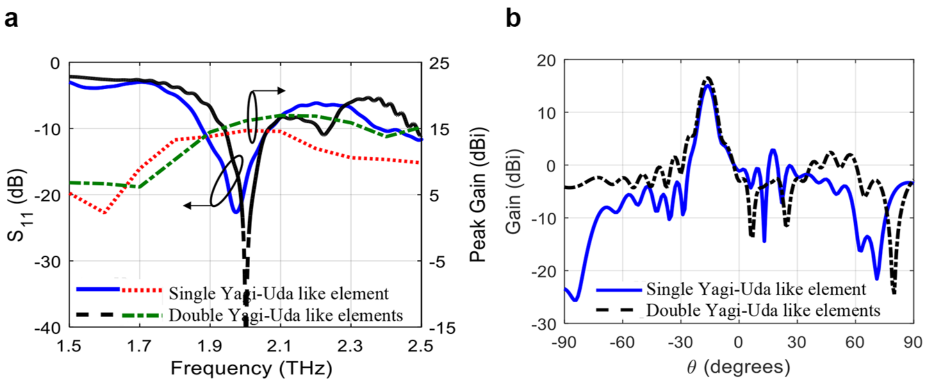

Fig. 9 (**a**) The S_{11} and peak gain versus frequency, (**b**) The gain pattern versus angle at 2 THz for the GS-LWA fed by single and double Yagi-Uda like elements at y-z plane

2.4 GS-LWA Fed by Tapered Microstrip Line

In this part, a conventional tapered microstrip line increases the antenna bandwidth with improved impedance matching. The impedance of the tapered microstrip line depends on the width, substrate thickness and dielectric constant with line lengths of $\lambda/4$ [28]. A tapered microstrip line is used to feed the GS-LWA as shown in Fig. 10a. The characteristic impedance is designed to be 50Ω. Transmission line with dimensions,$w_{s_1} = 74\mu m$, $L_{tap} = 76\mu m, L_{s_1} = 19\mu m, and w_{s_2} = 200\mu m$ is used. It lunches a plane wave to the GS-LWA that introduces BW 39.57% from 1.5 THz to 2.24 THz and peak gain of 17.5 dBi as shown in Fig. 10b.

The 3D gain patterns of the GS-LWA excited with different feeding mechanisms at 2 THz are plotted in Fig. 11. The beams are directed in θ=-16° direction with different values of the side lobes and back-lobes. Tapered microstrip line introduces the optimum feeder in terms of low side-lobes and minimized back-lobe. Both single and double Yagi-Uda elements introduce high side-lobes and back-lobes compared with other feeders. The E- field distri-

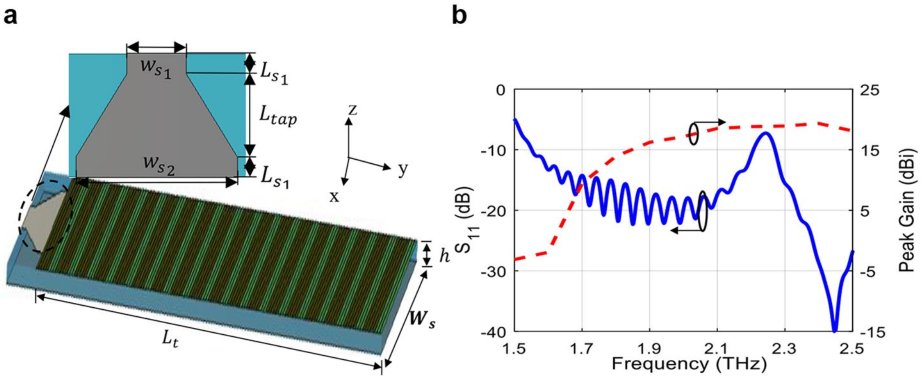

Fig. 10 Proposed structure of tapered Microstrip line for both cases of unloaded and loaded with GLWA. (**a**) The 3D array structure, (**b**) The S11 and gain versus frequency

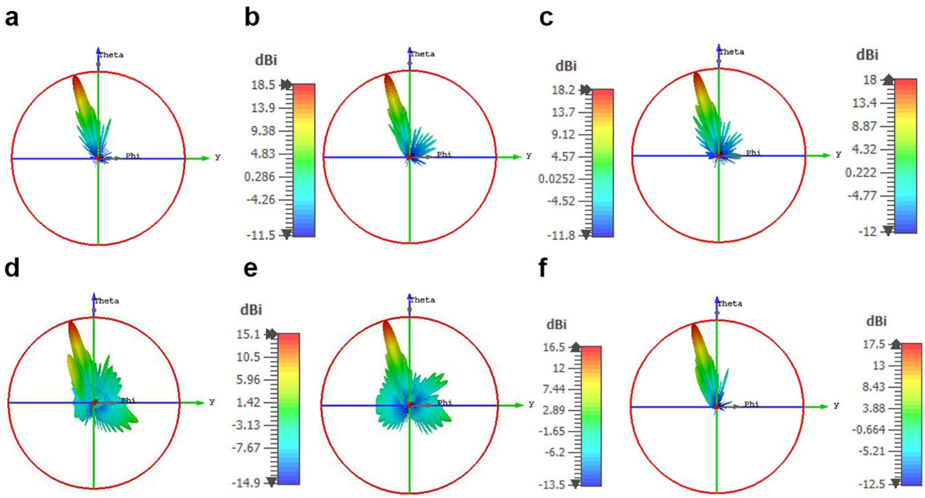

Fig. 11 3D gain patterns of the GS-LWA fed by different techniques at $f = 2.0THz.$. (**a**) Ideal wave port (**b**) SIWH horn (**c**) Parabolic reflector (**d**) Single Yagi element (**e**) Two Yagi elements (**f**) Tapered Microstrip line

Table 1 Comparison between the radiation characteristics of GS-LWA with different feeding methods

Feeding Structure	Ideal wave port	SIWH-horn antenna	Parabolic reflector	Yagi-Uda Like port	Yagi-Uda Like Array port	Tapered Microstrip line
Main beam angle (degree)	-16	-16	-16	-16	-16	-16
Peak gain (dBi)	18.5	18.2	18.0	15.1	16.5	17.5
HPBW (degree)	6.4	6.4	6.4	6.5	6.7	6.5
SLL (dB)	-11.6	-10.6	-10.6	-12.2	-10.9	-16.1
BW%	34% (1.56–2.2) THz	21.95% (1.72–2.15) THz	39.8% (1.65–2.47) THz	9.62% (1.88–2.07) THz	6.0% (1.94–2.06) THz	39.57% (1.5–2.24) THz

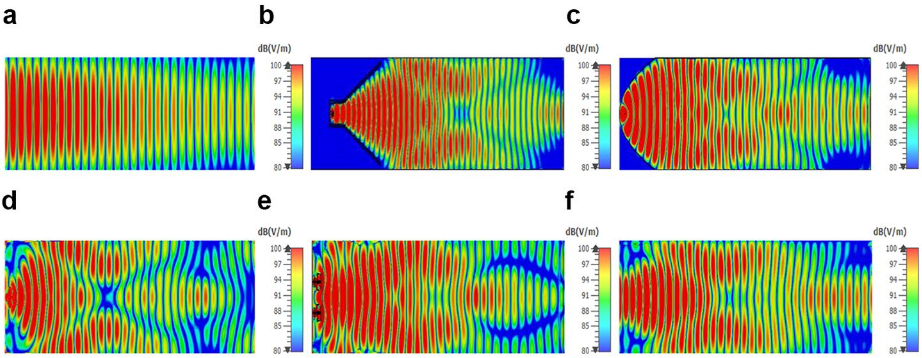

Fig. 12 Comparison between electrical field distributions at $f = 2.0THz.$. (**a**) Ideal wave port (**b**) SIWH horn (**c**) Parabolic reflector (**d**) Single Yagi element (**e**) Two Yagi elements (**f**) Tapered Microstrip line

butions on the GS-LWA with different feeders at 2 THz are shown in Fig. 12. Plane wave distributions are noticed to be launched from different feeders. Table 1 lists a comparison between the radiation characteristics of the GS-LWA with different feeding methods.

3 Conclusion

This paper investigates the radiation characteristics of GS-LWA fed using different feeding structures. The radiation characteristics of GS-LWA fed by the ideal wave - port is studied as a reference for other feeding structures. The radiated beam at $\theta =$-16^{o} direction with HPBW=6.4^{o} and SLL=-11.6 dB is obtained. The impedance matching bandwidth (BW) is 34% with peak gain of 18.5 dBi. Different feeding structures are investigated such as SIWH planar horn, planar parabolic reflector, Yagi-Uda like dipole, and tapered microstrip antenna. All the feeding structures lunches plane wave to the GS-LWA at different frequencies. The impedance matching BW is affected by the feeding mechanism type. The parabolic reflector introduces the widest BW of 39.8%, while Yagi-Uda like dipole array element has the narrowest BW of 6%. The peak gain varies from 15.1 dBi to 18.5 dBi according to the feeder. At 2 THz the antenna radiates the beam toward – 16^{o} direction and unaffected by the feeding type. The parabolic reflector and the tapered microstrip line introduce the optimum feeder for GS-LWA in terms of BW, peak gain, SLL, and reduced back radiation.

Author contribution All the authors contribute equally in this paper. S. Zainud-Deen and H. Malhat proposes the array structure, interpret results. N. Al-shalaby and A. Elhenawy perform results simulations and literature survey. All the authors are reviewed, analyzed and share paper proofreading.

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Data Availability There are no supplementary materials, and the data is available upon reasonable request.

Code Availability The program is available upon request.

Declarations

Ethics Approval Not applicable.

Conflict of interest The authors have no conflicts of interest or competing interests to declare that are relevant to the content of this article.

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