Electronic Supplementary Material (ESI) for Nanoscale.

Supplementary Information

Tunable wideband slot antenna based on printable graphene inks

Xiaoxiao Chen,[a,e] Xu Liu,[b,e] Shouhao Li,[b] Weimin Wang,[a] Di Wei,*[b] Yongle Wu*[a] and Zhongfan Liu*[b,c,d]

a. School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China. E-mail: wuyongle138@gmail.com

b. Beijing Graphene Institute, Beijing, China. E-mail: diwei@hotmail.com

c. Beijing National Laboratory for Molecular Sciences, College of Chemistry and Molecular Engineering, Peking University, Beijing 100871, P. R. China. E-mail: zfliu@pku.edu.cn

d. Center for Nanochemistry, Beijing Science and Engineering Center for Nanocarbons

e. Authors contributed equally to this work

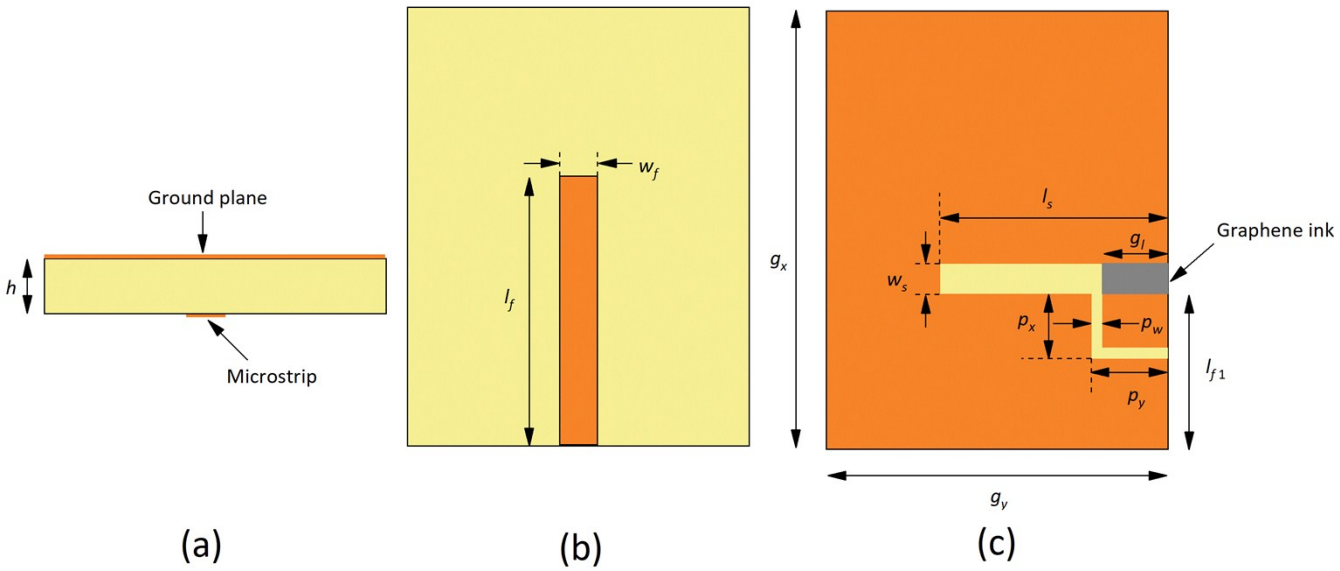

Fig. S1 Geometry of the proposed antenna. (a) Side view. (b) The microstrip. (c) The ground plane. The geometrical parameters of the proposed slot antenna are listed in Table S1.

Table S1 Dimensions of the slot antenna.

Parameters	h	g_x	g_y	l_f	w_f	l_{f1}
Value/mm	0.8	25	15	15.7	2.15	8.05
Parameters	l_s	w_s	p_x	p_y	p_w	g_l
Value/mm	11	2.2	3.55	3.2	0.2	3

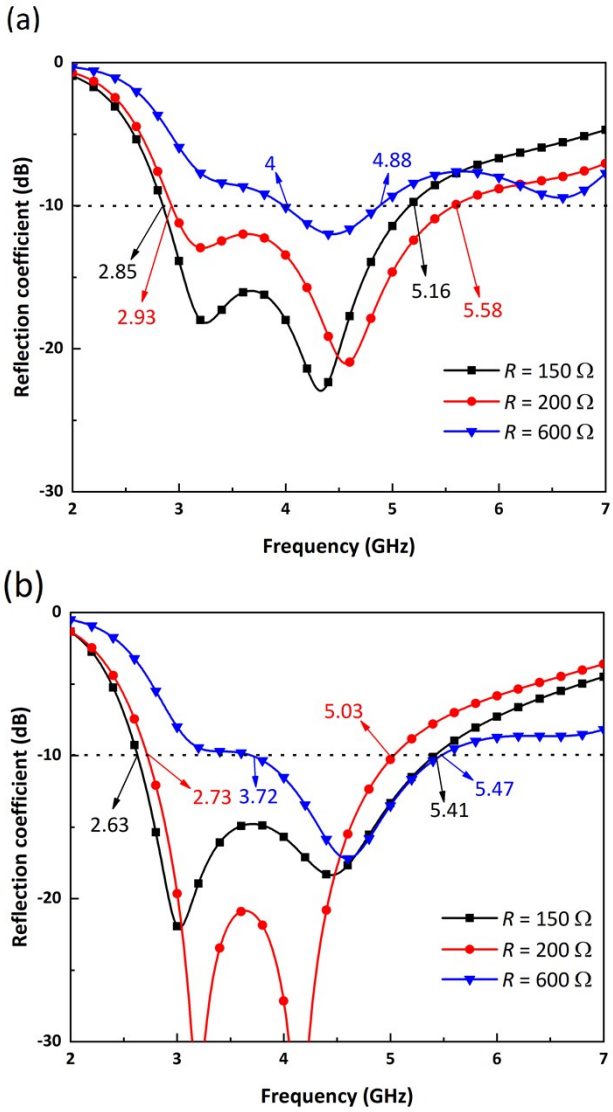

Fig. S2 Simulated reflection coefficients for the antenna contained graphene ink with different lengths. (a) g_l = 1 mm. (b) g_l = 2 mm.

Considering the influence of geometrical variation of the graphene ink on antenna performances, the area of the graphene inks was firstly studied by post-simulations. The reflection coefficients ($|S_{11}|$) for antennas contained graphene with different lengths (g_l = 1 mm, 2 mm, and 3 mm) were simulated at different resistances. The effective range of graphene resistance is from 150 Ω to 600 Ω in simulation. As shown in Fig. 1b and Fig. S2, it can be seen that the operational bands of the slot antenna with different g_l all shift towards higher frequency with the increase in resistance. However, the scale of shifts and operating bands were different. With g_l = 1 mm, the antenna operated at the band from 2.85 GHz to 5.16 GHz (an operating bandwidth of 2.31 GHz) with a 150 Ω graphene and operated at 4 GHz to 4.88 GHz (an operating bandwidth of 0.88 GHz) when the graphene was 600 Ω. While, the antenna with g_l = 3 mm operated at the band from 2.5 GHz to 5.13 GHz (an operating bandwidth of 2.63 GHz) when the graphene resistance was 150 Ω and operated at 2.97 GHz to 5.68 GHz (an operating bandwidth of 2.71 GHz) with a 600 Ω graphene ink. Noting that the area of graphene not only affected the variation of operating bandwidth, but also influenced the shift in resonant frequency. Although a smaller g_l of dried graphene ink resulted in a more apparent change in operating bandwidth, the larger g_l guaranteed a wider bandwidth. Therefore, for the sake of tuning in 5G frequency band, the g_l = 3 mm was chosen as the optimum parameter.

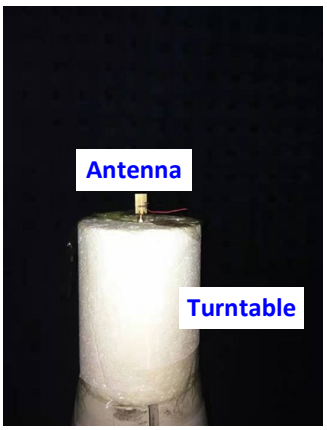

Fig. S3 The measurement setup of far-field performance of the antenna in microwave anechoic chamber.

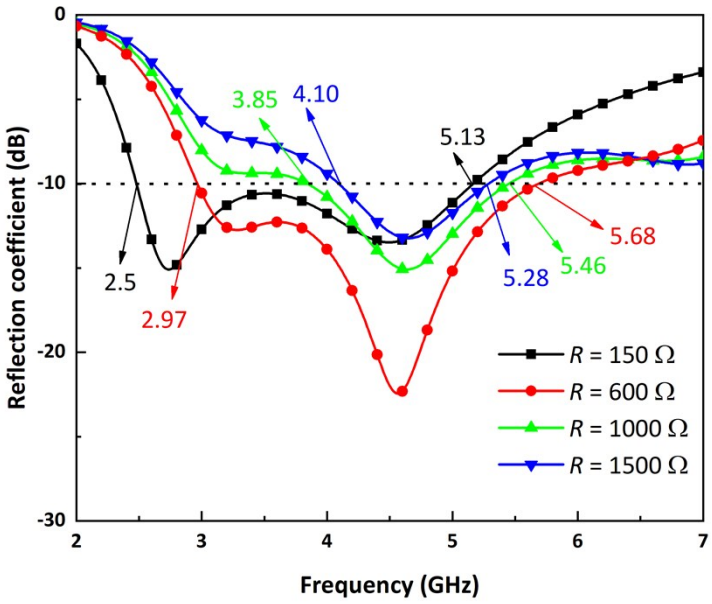

Fig. S4 Simulated reflection coefficients versus frequency for graphene inks with different original resistances.

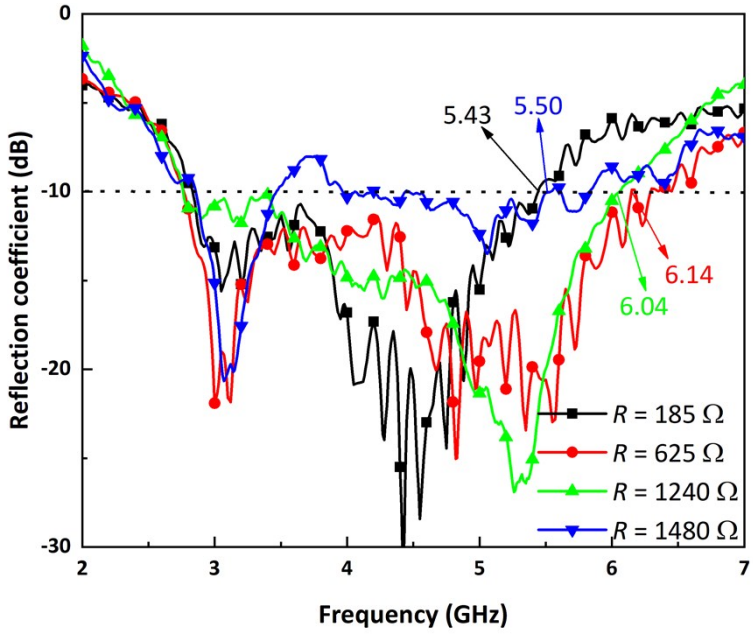

Fig. S5 Measured reflection coefficients versus frequency for graphene inks with different original resistances.

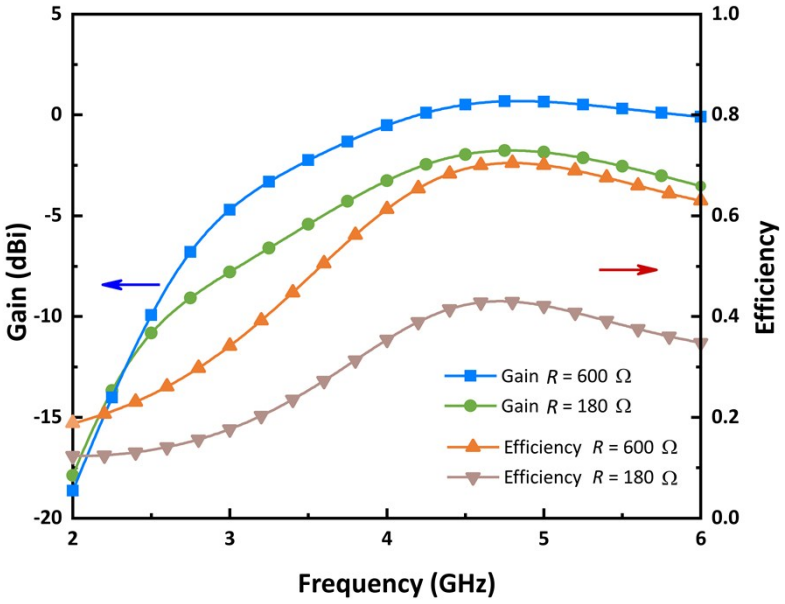

Fig. S6 Simulated boresight gains and efficiencies of the antenna versus frequency at different resistances.

a) In simulation, we use HFSS to simulate the efficiency of the antenna. In HFSS, the radiation efficiency is the ratio of the radiated power to the accepted power given by $e = \frac{P_{rad}}{P_{acc}}$.

Where

• P_{rad} is the radiated power in watts.

• P_{acc} is the accepted power in watts.

b) Gain is four pi times the ratio of an antenna's radiation intensity in a given direction to the total power accepted by the antenna. The following equation is used to calculate gain in HFSS:

$$gain = 4\pi \frac{U}{P_{acc}}.$$

where

• U is the radiation intensity in watts per steradian in the direction specified.

• P_{acc} is the accepted power in watts entering the antenna.

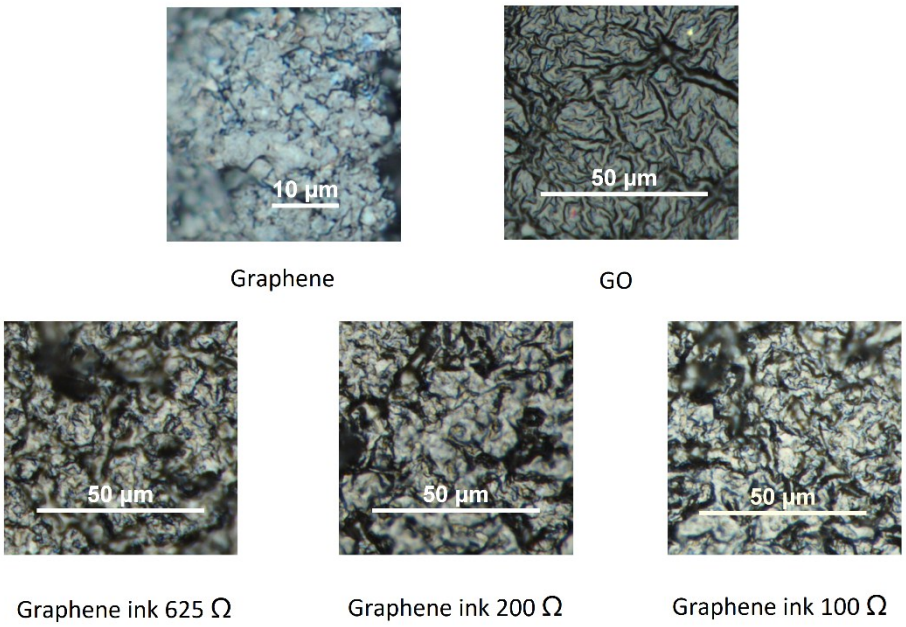

Fig. S7 The optical microscope images of GO, graphene powder, and graphene ink.

Table S2 Comparisons of the performance with reconfigurable antennas based on CVD graphene.

Refs.	Operating bandwidth or center frequency (GHz)	Frequency shift (MHz)	Bias voltage (V)	Bias circuits or tees	Fabrication of graphene materials	Size (mm^2)
25	8 - 12	24	–200 - 50	Yes	CVD	23×23
26	9.3 - 10.435	7.5	–20 - 0	Yes	CVD	15.4×10.85
27	5	550	0 - 5	Yes	CVD	51×56*
43	1.55	N. A.	–1 - 1	Yes	CVD	N. A.
This work	2.83 - 6	540	0 - 15	No	Printable ink	25×15

*Estimated value; N. A.: Not available/applicable.