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Tuning the Filter Responses with Graphene Based Resonators

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***Abstract*—Graphene-metal combined waveguide resonators were proposed earlier, as a solution for obtaining frequency tunable resonator responses at the sub-millimeter-wave frequencies. A methodology for combining these waveguide resonators into the frequency tunable filters has been studied subsequently. Here, we discuss the possibilities and limitations of this type of waveguide resonators, illustrated by several examples of tunable filter designs.**

Keywords—Tunable components and circuits, tunable filters (BPF), design method, sub-millimeter wave, graphene, full-wave numerical model, equivalent circuits

I. INTRODUCTION

Submillimeter (low-terahertz) wave region of electromagnetic (EM) spectrum is, in addition to numerous applications in astrophysics, remote sensing, spectroscopy and imaging [1], [2], currently being investigated for other uses as well, including the beyond 5G future broadband communications [3]. Novel components and circuits are also being proposed, often relying on the design approaches using micromachining, metamaterials, new materials such as graphene, etc. In line with these current trends, we have proposed and studied the tunable graphene-metal combined waveguide resonators [4], where the graphene has been employed in order to achieve frequency tunability. Due to the nonlinear frequency dependence, around the desired central frequency, of the equivalent analytical models of *E*-plane discontinuities as well as pronounced losses in graphene, an accurate analysis required the full-wave EM numerical computations [4]. The state-of-the-art commercial software package HFSS has been employed in the design procedures relying on the extensive design space mapping [5]. The variable surface conductivity of graphene has been modeled, in the considered frequency range where the spatial-dispersion effects are negligible, using the Kubo formalism of statistical physics [6]:

$$\sigma(\omega,\mu_c,\Gamma,T) = \frac{-jq_e^2 k_B T}{\pi\hbar^2(\omega - j2\Gamma)}\left(\frac{\mu_c}{k_B T} + 2\ln\left(e^{-\frac{\mu_c}{k_B T}} + 1\right)\right). \quad (1)$$

Here, we outline the general design procedure, described in detail in [5], and illustrate the design of graphene tunable filters by using several examples of filters at 400 GHz. Obtainable filter responses mostly depend on the required bandwidth and tunability in combination with the acceptable insertion loss. Parameters such as the required filter order and maximal passband ripple level have to be adopted accordingly. Tabulated data for several filter responses is used to provide insight into the typical values of bandwidth, tunability and losses that can be achieved jointly.

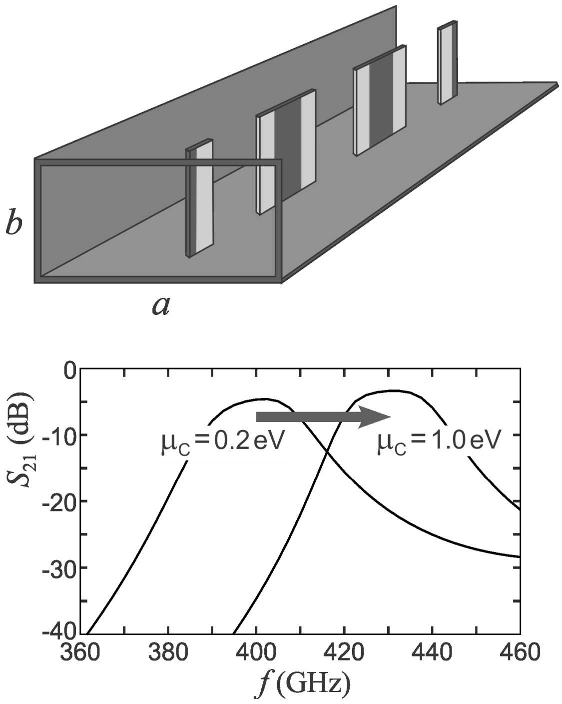

Fig. 1. Graphene based tunable filter (top). Electrostatic bias field can be utilized to influence the chemical potential of graphene, μ_c, further changing the surface conductivity of graphene. Correspondingly, the boundary conditions at the edges of graphene-metal combined *E*-plane discontinuities are varied, leading to the effects similar to varying the effective lengths of resonators. Tunable filter respones are obtained (bottom). A design procedure for obtaining the desired filter responses is explained.

II. DESIGN PROCEDURE

A. Tunable resonator responses

Due to the linearly increasing inductive component of graphene surface conductivity with the increase in frequency, it is proven to be a good electromagnetic material for low-terahertz and terahertz frequencies. Graphene based waveguide resonators were studied at frequencies from 100 GHz up to 1100 GHz [4]. The achievable tunability range for resonators completely covered with graphene, for the studied insert length of $0.324a$, increased from 4% to about 12% with increase in frequency. Likewise, the insertion loss decreased [4]. However, loaded quality factors were lower than those in the metallic resonators. In the graphene-metal combined waveguide resonators, the quality factors were improved and at higher frequencies comparable with the metalic resonators. Reasonable tunability of 5% to 6% was obtained for the graphene stripe width of 25% of an *E*-plane insert.

B. Design space mapping

Operation of graphene based resonators relies on the modification of an effective resonator length. Namely, the equivalent circuit of a combined graphene-metal resonator can be conveniently represented using the K-inverter circuit with an equivalent gain K, and an equivalent electrical length at ports, ϕ. For the chemical potential between 0.2 eV and 1.0 eV, parameter K ("gain") predominantly depends on the insert length [5]. The equivalent electrical length, ϕ, strongly depends on the material properties. Larger variation of ϕ is observed for larger insert lengths.

Initially, design space mapping was performed for a number of combinations of *E*-plane insert lengths and lengths of graphene covered insert parts. It is performed in a range of frequencies of interest, so as to also enable interpolating the data in between the calculated data points. The collected data sets were utilized to determine the geometrical loci of points (combinations of insert lengths and graphene lengths) with the desired gains, K. Also, based on the collected data, the appropriate quantity of graphene to achieve the desired tunability can be determined. This is explained in much more detail in [5].

C. Filter design

The change in parameter ϕ, following the increase of the chemical potential from 0.2 eV to 1.0 eV, depends on the used combination of insert length and graphene stripe length. The physical lengths of resonators are fixed; therefore, the change in ϕ is compensated for by the resonant frequency shift towards the higher frequencies. A set of curves taking into account such shifts is prepared and compared with the normalized guided wavelength variation with frequency. A particular curve is adopted as a solution based on an estimated tunability. For more detailed explanation, as well as the graphical representation, please see [5].

III. FILTER DESIGN EXAMPLES

Several design examples are prepared here to illustrate the design procedure. First, a relatively narrowband filter example is considered. The achieved bandwidth in this case was 4%. The corresponding dimensions for the third order filter, and the allowed ripple level of 0.01 dB, were 400 μm for a total length of each of the two inner waveguide resonators, and 190 μm for a total length of each of the two outer waveguide resonators. Inner graphene stripes were 110 μm wide, whereas outer graphene stripes were 80 μm wide. The obtained tunability in this case was very good (8.64%); however, the losses were somewhat high due to a large quantity of graphene.

Other examples used the same ripple level: 0.01 dB was allowed. The achieved bandwidth in the second example was 6%. The corresponding dimensions were 310 μm and 170 μm for total lengths of each of the two inner and outer waveguide resonators, respectively. Both the inner and the outer graphene stripes were 80 μm wide, providing the 7.4% tunability.

TABLE I. FILTER DESIGN EXAMPLES

Example Filter	**Characteristics**		
	Bandwidth (%)	***Tunability (%)***	***Insertion loss (dB)***
3rd order	4.0	8.64	6.4
3rd order	6.0	7.40	2.2
3rd order	10.0	8.00	3.0
5th order	5.2	5.80	5.2

The third example of a third order filter had 270 μm and 90 μm long inner and outer inserts, respectively, with the 80 μm and 40 μm wide graphene stripes. This helped achieve 10% bandwidth and 8% tunability with the loss of about 3 dB. Finally, a fifth order filter design is presented, with the insert lengths of 170 μm, 120 μm, and 30 μm, starting from the innermost. The appropriate lengths of graphene were 70 μm and 30 μm (outer ones). Much sharper filter response was obtained, with the attained bandwidth of 5.2% and tunability of 5.8%. Main filter response characteristics are listed in Table I.

IV. CONCLUSIONS

With careful planning, even the filter responses achieved by the 3rd order filters were satisfactory. The losses for individual resonators and the entire filter are comparable due to the outer inserts being a dominating source of losses. The design methodology is simple and it can be successfully utilized to design the filter responses of various characteristics.

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