Integrated waveguide filter amplifier using the coupling matrix technique

Gao, Yang; Shang, Xiaobang; Guo, Cheng; Powell, Jeff; Wang, Yi; Lancaster, Michael J.

DOI:
10.1109/LMWC.2019.2901892

Citation for published version (Harvard):
Gao, Y, Shang, X, Guo, C, Powell, J, Wang, Y & Lancaster, MJ 2019, 'Integrated waveguide filter amplifier using the coupling matrix technique', *IEEE Microwave and Wireless Components Letters*, vol. 29, no. 4, 8667432, pp. 267-269. https://doi.org/10.1109/LMWC.2019.2901892

Integrated Waveguide Filter Amplifier using the Coupling Matrix Technique

Yang Gao, Xiaobang Shang, Jeff Powell, Cheng Guo, Yi Wang, *IEEE, Senior Member*,
Michael J. Lancaster, *IEEE*, *Senior Member*

***Abstract*—This letter presents an integrated waveguide filter-amplifier using all resonator-based filtering and matching structure. An *N*+4 active coupling matrix is proposed for the first time to describe the coupling topology. High-*Q* waveguide resonators are featured in the design achieving simultaneous filtering and matching at both the input and output ports. Easy integration of the transistor with waveguide resonators is demonstrated through filter synthesis, where a hybrid waveguide/microstrip structure is implemented for the structural and impedance transition. Here in this work, the presented X-band device is constructed as a demonstrator, but the technique is also applicable to higher frequencies where waveguide is widely utilized for its lower loss.**

***Index Terms*—Active coupling matrix, transistor, resonator, waveguide filter amplifier.**

I. Introduction

Filters and amplifiers are often designed separately with a 50 Ω impedance interface and then assembled. Planar matching networks are required for an amplifier in order to attain the 50 Ω impedance. Losses are assocaited with the planar circuit matching, filtering and transition circuit, which can be significant when the frequencies rise to the submillimetre-wave band. Thus, high *Q*-factor waveguide-based components become appropriate choices for submillimetre-wave or terahertz applications [1], [2]. In addition, integrating the filters with the amplifier yields reduced component size, weight and circuit complexity through removing intermediate transitions and impedance matching. A co-design approach is proposed here, where the low loss waveguide filter is directly coupled to the input and output of the transistor without using any microstrip matching circuits.

To do this, two filtering structures are presented both at the input and output of the transistor and the overall structure can be represented using an active *N*+4 (*N* is the number of the resonators) coupling matrix. This is a significant progress compared to our previous work with just an input filter with an *N*+3 matrix in [2]. Complex valued input and output impedances of the transistor are matched simultaneously, achieving Chebyshev S_{11} and S_{22} as well as a S_{21} response with a gain over the passband. Compared to [2], not only the input but also the output of the transistor is matched using waveguide filter, which allows that the rectangular waveguide can be applied throughout systems and the assembled ports of devices made with waveguide end to end.

This work was supported by the UK Engineering and Physical Science Research Council (EPSRC) under Contract EP/M016269/1. The authors are with the Department of Electronic, Electrical and Systems Engineering, University of Birmingham, Birmingham, B15 2TT, United Kingdom. Corresponding author: Cheng Guo (Email: spmguo@163.com).

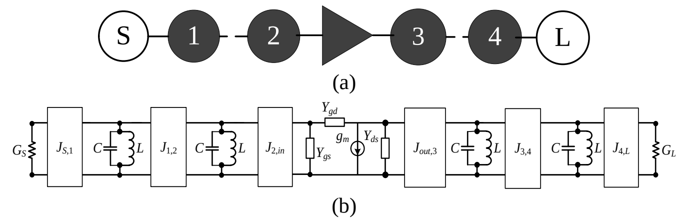

Fig. 1. Topology and equivalent circuit of the transistor with input and output resonator matching. (a) Schematic representation of the circuit. (b) Lumped circuit model. G_S and G_L are the source and load conductance; Y_{gs}, Y_{gd}, and Y_{ds} are the admittances between transistor's gate, source and drain; g_m is the transconductance.

Fig. 1(a) shows the filter-amplifier schematically, with the clear circles representing the source and load, and the solid black circles denoting the resonators. This can be translated into a small signal lumped circuit, with the transistor coupled to the filters via *J* inverters at the gate and the drain, as shown in Fig. 1(b). Here we have *N*=4 for the circuit, but clearly *N* can be extended to more resonators if required. This circuit can be used to determine an *N*+4 coupling matrix.

Given the required filter specification and the transistor's parameters, the values in the *N*+4 matrix for the filter-amplifier can be found analytically. From this active coupling matrix, the *S*-parameter responses and the gain can be predicted. The matrix also provides the basis for the design of the physical structure in a similar manner to the design of conventional filters using the coupling matrix [3].

II. Active *N*+4 Coupling Matrix

Based on the *N*+2 coupling matrix theory described in [4], and the active *N*+3 coupling matrix synthesized in [1], the *N*+4 active coupling matrix representing the integrated filter amplifier can be written as

$$[m]=\begin{bmatrix} 0 & m_{S,1} & 0 & 0 & 0 & 0 & 0 & 0 \\ m_{1,S} & 0 & m_{1,2} & 0 & 0 & 0 & 0 & 0 \\ 0 & m_{2,1} & m_{2,2} & m_{2,in} & 0 & 0 & 0 & 0 \\ 0 & 0 & m_{in,2} & 0 & m_{in,out} & 0 & 0 & 0 \\ 0 & 0 & 0 & m_{out,in} & 0 & m_{out,3} & 0 & 0 \\ 0 & 0 & 0 & 0 & m_{3,out} & m_{3,3} & m_{3,4} & 0 \\ 0 & 0 & 0 & 0 & 0 & m_{4,3} & 0 & m_{4,L} \\ 0 & 0 & 0 & 0 & 0 & 0 & m_{L,4} & 0 \end{bmatrix} \tag{1}$$

In (1), $m_{i,j}$ represent the inter-resonator coupling; $m_{S,1}=m_{1,S}$ and $m_{L,4}=m_{4,L}$ are the external couplings from the resonators to the source and load; $m_{2,in}=m_{in,2}$ and $m_{out,3}=m_{3,out}$ are the couplings from the resonators to the transistor's gate and drain, respectively. $m_{in,out}$ and $m_{out,in}$ are the couplings between the transistor's input and output. They are given in terms of the transistor parameters as [2],

$$m_{in,out} = -j\cdot \bar{Y}_{gd}, \quad m_{out,in} = -j\cdot\left(\bar{Y}_{gd} - \bar{g}_m\right) \qquad (2)$$

Note that the transistor's parameters have been normalized to the identity port impedance of 1 Ω. The parasitic admittance between the gate and the drain Y_{gd} is assumed to be zero, because it is usually very small and can be neglected [5], [6]. The terms $m_{2,2}$, and $m_{3,3}$ in (1) denote the frequency shift of the asynchronously tuned resonators, adjacent to the transistor; namely, resonators 2 and 3 in Fig. 3. This allows the desired filter response to be maintained despite the complex impedance

TABLE I
VALUES OF THE NORMALIZED TRANSISTOR'S SMALL SIGNAL PARAMETERS

Y parameters	Values	Y parameters	Values
$\bar{Y}_{ds}$	0.2752+0.6367*j*	$\bar{g}_m$	3.4812-6.7500*j*
$\bar{Y}_{gs}$	0.2528+1.3799*j*	$\bar{Y}_{gd}$	0

All parameters are extracted from the data sheet [7] assuming the transistor operates at 10 GHz.

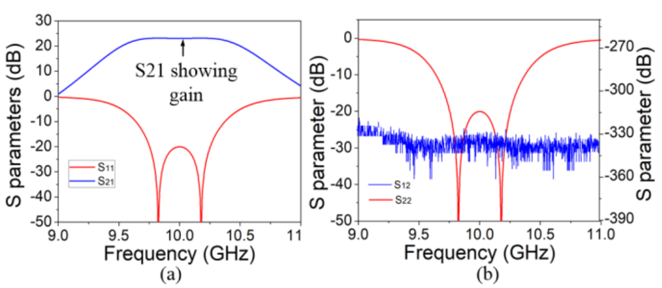

Fig. 2. Calculated filter-amplifier responses using the coupling matrix formulation. (a) S_{11} and S_{21}. (b) S_{22} and S_{12}.

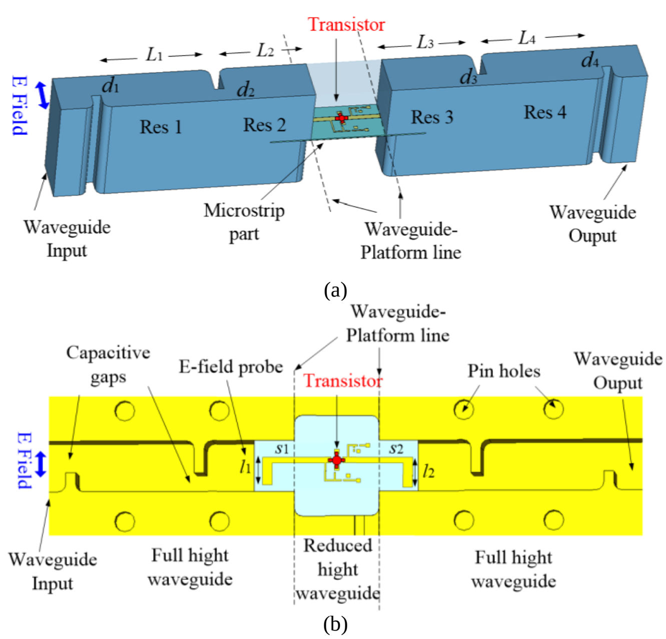

Fig. 3. Diagrams of the waveguide filter-amplifier. (a) 3D view of the waveguide air model with the microstrip circuit. (b) Sectional view of the waveguide filter and the on-chip transistor circuit.

of the transistor [2]. $m_{2,2}$ and $m_{3,3}$ are calculated by [2]

$$m_{2,2} = -\frac{\mathrm{Im}\left(\bar{Y}_{gs}\right)}{\mathrm{Re}\left(\bar{Y}_{gs}\right)\cdot q_{e2}}, \quad m_{3,3} = -\frac{\mathrm{Im}\left(\bar{Y}_{ds}\right)}{\mathrm{Re}\left(\bar{Y}_{ds}\right)\cdot q_{e3}} \qquad (3)$$

where q_{ei} is the normalized external quality factor of the i^{th} resonator [3]. Couplings between the transistor and the resonators can be expressed as [2]

$$m_{in,2} = m_{2,in} = \sqrt{\frac{\mathrm{Re}^2\left(\bar{Y}_{gs}\right)+\mathrm{Im}^2\left(\bar{Y}_{gs}\right)}{\mathrm{Re}\left(\bar{Y}_{gs}\right)\cdot q_{e2}}}$$
$$m_{out,3} = m_{3,out} = \sqrt{\frac{\mathrm{Re}^2\left(\bar{Y}_{ds}\right)+\mathrm{Im}^2\left(\bar{Y}_{ds}\right)}{\mathrm{Re}\left(\bar{Y}_{ds}\right)\cdot q_{e3}}} \qquad (4)$$

The other elements in [*m*] can be calculated for a conventional filter in the normal way from the standard filter *g*-values according to [3].

As an example, 2-pole Chebyshev filters are used to simultaneously match the input and output of a transistor. A center frequency f_0 of 10 GHz, a bandwidth of 500 MHz (fractional bandwidth *FBW* of 5%) and a passband return loss of 20 dB is used. According to the filter specification and (2)-(4), as well as the transistor parameters in Table I, the normalized *N*+4 coupling matrix [*m*] can be calculated as

$$[m] = \begin{bmatrix} 0 & 1.2264 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.2264 & 0 & 1.6621 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.6621 & -8.2104 & 3.4219 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3.4219 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 6.75+3.4812j & 0 & 1.6216 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.6216 & -3.4800 & 1.6621 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.6621 & 0 & 1.2264 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1.2264 & 0 \end{bmatrix} \qquad (5)$$

The corresponding *S*-parameters response of this coupling matrix (5) can be calculated [2], [3], and is shown in Fig. 2. It exhibits a Chebyshev response for S_{11}, S_{22} and S_{21} with the latter showing a gain as expected.

III. PHYSICAL DESIGN OF THE WAVEGUIDE FILTER-AMPLIFIER

The physical structure of the device consists of two waveguide resonator filters and a transistor mounted on a printed circuit board (PCB), as illustrated in Fig. 3. The PCB is placed on a platform in the middle of a reduced height waveguide. The transistors' gate and drain are coupled to resonator 2 and resonator 3 via the coupling probes with the lengths marked as l_1 and l_2. The microstrip circuit also include quarter-wavelength long (at 10-GHz center frequency) bias tees for DC connections.

The filter-amplifier design process resembles that of a conventional filter [3]. The first step is to determine the Q_e of resonators 1 and 4, as well as the inter-resonator couplings. The Q_e of resonators 1 and 4 can be derived from the coupling matrix (1) using

$$Q_{e1} = 1/\left(FBW\cdot m_{S,1}^2\right), \quad Q_{e4} = 1/\left(FBW\cdot m_{L,1}^2\right) \qquad (6)$$

The inter-resonator coupling $M_{i,j}$ is calculated by

$$M_{i,j} = FBW\cdot m_{i,j} \quad i, j\text{=1 to } N \qquad (7)$$

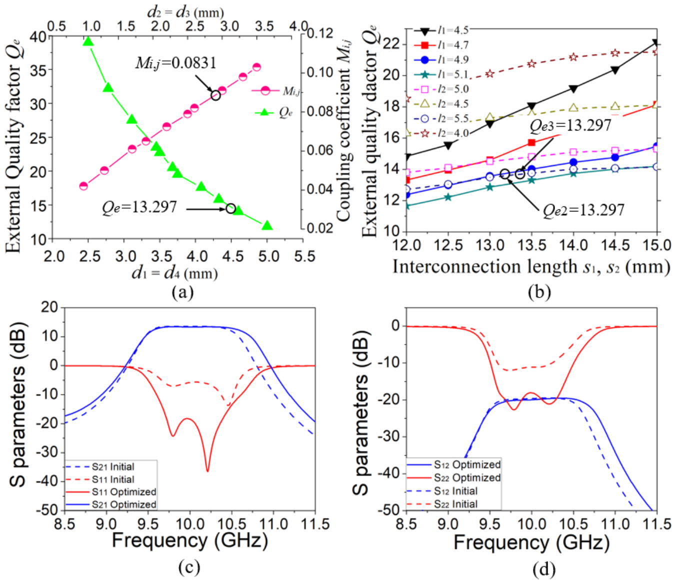

Fig. 4. (a) External quality factor Q_e versus dimension d_1, d_4; Coupling coefficient $M_{i,j}$ versus dimension d_2, d_3. (b) External quality factor Q_e versus dimension s_1, s_2. (c) Simulation response with initial and optimized values S_{11} and S_{21}. (d) S_{22} and S_{12}.

It can be seen from Fig. 3(a) that Q_e can be determined in practice by the gaps d_1 and d_4, whereas the inter-resonator couplings $M_{1,2}$ and $M_{3,4}$ are determined by dimensions marked as d_2 and d_3. The relationships between the Q_e (and $M_{i,j}$) and the corresponding physical dimensions can be found through full-wave simulations [3]. d_1=d_4=4.51, d_2=d_3=2.75 (mm) can be found from Fig. 4(a).

The next step is to determine the external quality factor Q_e of resonators 2 and 3, which are coupled to the transistor's input and output, respectively. The values of the required Q_e have been proven to be the same as a conventional filter [1], [3], and for our example are given by Q_{e2}=Q_{e3}=13.297. In order to find the correct lengths l_1, l_2, s_1 and s_2 to attain this value, a graph is drawn of Q_e verses the lengths [2]. This is shown in Fig. 4(b). Note the Q_e values in Fig. 4(b) already considered the transistor's input and output impedances, which are generally a non-50-Ω complex value. This design requires that resonators 2 and 3 (including the transistor's input and output impedances) resonate at the center frequency of the filter, which is achieved by adjusting the lengths of the resonators, L_2 and L_3. From Fig. 4(b), the required vales are l_1=4.9, l_2=5.5, s_1=13.22, and s_2=13.27 (mm).

The whole structure can now be simulated in CST using the initial values extracted above. The simulated operating conditions of the transistor are drain-to-source voltage V_{ds}= 2 V and drain current I_{ds} = 10 mA [7]. Optimization is performed by the EM simulator with the results shown in Fig. 4(c) and (d). Note that the optimized results are close to the initial results, demonstrating the potential of this technique.

IV. Fabrication and Measurements

The waveguide parts are made of aluminum (AL5400), and Duroid RT/5870 is utilized for the PCB. Fig. 5 shows a photograph of the device. Simulated and measured results are presented in Fig. 6. Bias condition of the transistor is provided by a gate-to-source voltage of V_{gs} =−0.56 V and drain-to-source voltage of V_{ds}=2.3 V. Results show two distinct reflection zeros in both the S_{11} and S_{22} responses, providing the evidence of the two-pole filtering characteristic. The measured S_{21} curve shows a filtering response with a gain of around 11 dB across. The general good agreement between measurement and simulation validates the co-design methodology using coupling matrix.

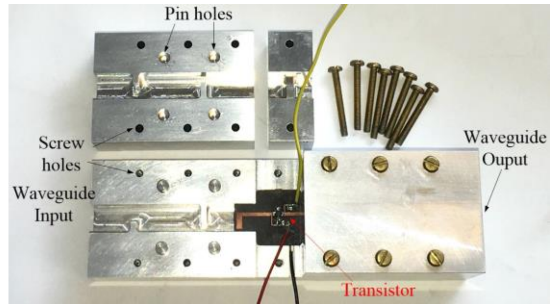

Fig. 5 Photograph of the fabricated waveguide filter-amplifier device.

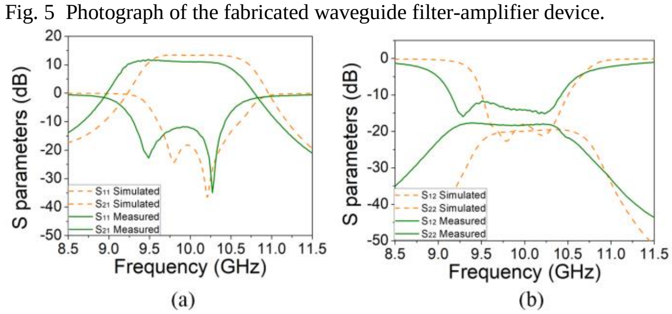

Fig. 6 Simulation (dashed lines) and measurement (solid lines) results. (a) Scattering parameters S_{11}, S_{21}. (b) Scattering parameters S_{22}, S_{12}.

V. Conclusion

This letter presents a novel active N+4 coupling matrix for a filter-amplifier. The N+4 matrix describes both filtering matching and the amplification of the device. Appropriate initial dimensions of the physical structure can be found from the coupling matrix, which can then be used for final optimization. Using this co-design approach, the conventional filter design method [3] can be extended to the design of amplifiers. The integration of the multi-functional circuits and the use of high-Q waveguide resonators brings a superior device in terms of low loss, simplicity and compactness. The technique will be valuable for the design of higher frequency amplifiers where losses from the on-chip circuits can be significant.

References

[1] H. Yang et al., "WR-3 waveguide bandpass filters fabricated using high precision CNC machining and SU-8 photoresist technology," *IEEE Trans. THz Sci. Techn.*, vol. 8, no. 1, pp. 100–107, Jan. 2018.

[2] Y. Gao, J. Powell, X. Shang and M. J. Lancaster, "Coupling matrix-based design of waveguide filter amplifiers," *IEEE Trans. Microw. Theory Techn.*.doi: 10.1109/TMTT.2018.2871122.

[3] J. S. Hong and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*. New York, NY, USA: Wiley, 2001.

[4] R. J. Cameron, R. Mansour and C. M Kudsia, *Microwave Filters for Communication Systems: Fundamentals, Design and Applications*. 1st. New York, NY, USA: Wiley, 2007.

[5] I. Bahl, *Fundamentals of RF and Microwave Transistor Amplifiers*. Hoboken, N.J.: Wiley, 2009.

[6] D. Pozar, *Microwave engineering*. Hoboken, NJ: Wiley, 2012.

[7] California Eastern Labotatories (2004, July). CEL Corp., CA. [Online]. Available: http://www.cel.com/pdf/datasheets/ne3210s1.pdf