

Artificial neural networks assisted analysis of an RF-MEMS switch for W-band applications

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Abstract – This paper presents an efficient approach for the analysis of a W-band RF-MEMS switch based on an artificial neural network (ANN) model of the switch return and insertion losses. The analysis is performed over the 92–95 GHz frequency range, with particular emphasis on the influence of the switch recess dimension. In the proposed ANN modeling approach, the recess dimension is used as the primary input parameter. Two separate ANN models are employed to capture the frequency dependence of the return and insertion losses. Moreover, a power flow analysis is carried out by converting the modeled return and insertion losses into reflected, transmitted, and absorbed power components. The developed ANN model enables fast and accurate evaluation of loss characteristics and power distribution, facilitating efficient parametric studies and design optimization of W-band RF-MEMS switches.

Keywords – Artificial Neural Networks, Insertion Loss, Return Loss, RF-MEMS Switch, Power.

I. INTRODUCTION

The forthcoming 6G communication standard is expected to deliver unprecedented user-experienced performance, with downlink data rates ranging from 300 Mb/s to 100 Gb/s and peak rates potentially reaching 200 Gb/s – 1 Tb/s, significantly exceeding 5G capabilities [1]. In addition to throughput, newly introduced key performance indicators (KPIs) emphasize energy sustainability, targeting a reduction of Radio Access Network (RAN) energy consumption by 15–50% compared to 5G [1]. Achieving these ambitious objectives will require operation over higher and wider frequency bands and the deployment of massive multiple-input multiple-output (mMIMO) systems, whose power consumption scales with array size [2]. Consequently, future radio resources are expected to extend beyond current 5G allocations toward millimeter-wave and sub-THz frequencies [3], including the W-band (75–110 GHz), which is particularly attractive for high-data-rate indoor communications.

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At these frequencies, the intrinsic limitations of silicon-based active devices become increasingly severe, motivating the adoption of passive and low-power RF front-end solutions. In this context, radio-frequency microelectromechanical systems (RF-MEMS) represent a promising technology for compact, broadband, and energy-efficient components, such as switches, phase shifters, and reconfigurable networks [4], [5]. The use of wide bandgap materials, such as silicon carbide (SiC) [6], can further enhance RF-MEMS reliability by improving mechanical robustness and mitigating issues related to stiction and structural degradation [7].

For W-band operation, RF-MEMS switch performance is critically affected by parasitic capacitances, contact resistance, and coplanar waveguide (CPW) discontinuities. To address these challenges, a clamped–clamped RF-MEMS switch topology is adopted in this work. The symmetric anchoring of the beam enables a short and well-defined interaction region with the CPW signal line, reducing parasitic loading and enabling effective impedance control over a wide bandwidth. In series configurations, this topology provides a stable and repeatable contact interface, which is essential for achieving an ON-state insertion loss below 1 dB and a return loss better than 10 dB across the W-band. Although a higher actuation voltage is required compared to cantilever-based designs, the resulting improvements in RF performance make the clamped–clamped topology well suited for low-loss, energy-efficient RF-MEMS switches targeting future W-band wireless systems.

Artificial intelligence is also emerging as a key enabler for future communication systems. Beyond its anticipated role in large-scale network optimization, artificial intelligence has recently demonstrated significant potential in device-level design and optimization. Full-wave numerical techniques, such as finite element method (FEM)–based electromagnetic simulators, are commonly used to characterize RF-MEMS switch performance; however, their computational cost becomes prohibitive when extensive parametric analyses are required [8]. Artificial neural networks (ANNs) provide an effective alternative, as they can learn complex relationships between device parameters and performance metrics, enabling rapid and accurate prediction of RF and mechanical behavior [9]. This capability has led to widespread adoption of ANNs in RF, microwave, and millimeter-wave applications, including the electro-

magnetic optimization of RF-MEMS switches up to the K band [10], Ka band [11], [12], joint electromechanical optimization [13], and antenna design [14].

Beyond sub-THz considerations, lower frequency bands are also expected to play a key role in future spectrum expansion. In particular, the W-band, including the 71–76 GHz, 81–86 GHz, and 92–95 GHz ranges [15], represents a strong candidate for high-data-rate indoor communication scenarios [16]. In this context, reliable SiC-based RF-MEMS switches offer a compelling solution for realizing low-power, broadband, and high-performance RF front-end components suitable for next-generation wireless systems.

The design process assumes a thorough analysis of the device performance and optimizations to achieve the desired design targets. Performing simulations in full-wave simulators may require a significant amount of time. Owing to their short response time, the ANN models become an efficient alternative for fast and efficient simulations and analysis of the switch characteristics.

In this paper, ANN assisted analysis of a SiC-based RF MEMS switch return and insertion losses are exemplified. The analysis is done by using the switch ANN model developed for the 92–95 GHz frequency range, recently presented in [17], which incorporates the dependency of the S-parameters on the switch recess. Section II describes the device layout designed using the Fondazione Bruno Kessler (FBK) in-house fabrication technology and introduces the ANN model used for the analysis. The outcomes of the ANN based analysis of the switch return and insertion losses are given in Section III. Section IV reports the outcomes of the ON-state power flow analysis. Finally, Section V provides the concluding remarks.

II. RF MEMS SWITCH MODEL

The SPST (Single-Pole-Single-Throw) layout is based on the 8-mask in-house fabrication technology at FBK facility, with a small modification to account for the introduction of SiC as structural material in the MEMS membrane. In particular, beyond the 525 μm -thick silicon substrate and the 2.66 μm -thick insulating layer of silicon oxide, the CPW transmission line and most of the MEMS bridges is composed by gold metallization [17]. The first is a 150 μm -thick layer of evaporated gold (in yellow in Fig. 1), forming the areas of landing for the membrane and the foundation of the following layers: a first 2 μm -thick layer (in grey) and a second 3 μm -thick layer (in orange) of electroplated gold composing the CPW structure. Concerning the structure of the movable membrane, the basic fabrication technology envisioning the 2 μm -thick structural layer of electroplated gold (in grey) has been modified by substituting it with a 1.5 μm -thick core of amorphous SiC, patterned by 250 nm of electroplated gold on both sides (2 μm in total). The second layer of electroplated gold is meant to enforce an overall planarity to the membrane.

Regarding the parameters ruling the model, it has been

parametrized based on the recess dimensions and the dimensional features of the CPW transmission line, as visible in Fig. 1 [17]. In this first investigation, the focus has been put on the RF matching between the CPW structure and the membrane, so that the initial simulations have been performed by varying the recesses' dimensions, leaving untouched the width of the signal line and the gap, amounting to 90 and 52 μm , respectively.

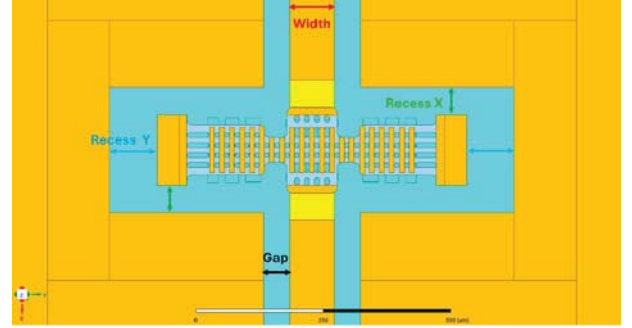


Fig. 1. Layout of the proposed switch [17].

In RF and microwave engineering, the performance of a device such as an RF-MEMS switch is often characterized using S-parameters that describe the relationship between incident and reflected waves at the device ports.

Return loss (RL) and insertion loss (IL) are commonly measured quantities in decibels (dB) that relate directly to S-parameters. Namely, RL quantifies how much of the incident power is reflected at a port:

$$RL(\text{dB}) = -20 \cdot \log(|S_{11}|) = -10 \cdot \log(|S_{11}|^2), \quad (1)$$

i.e., show how much power never enters the DUT (Device Under Test). Therefore, the fraction of the incident power reflected at port 1 is:

$$|S_{11}|^2 = 10^{RL(\text{dB})/10}. \quad (2)$$

IL quantifies the loss of power through the device from input to output:

$$IL(\text{dB}) = -20 \cdot \log(|S_{21}|), \quad (3)$$

i.e., it determines how much of the incident power reaches the output. The fraction of incident power delivered to port 2 is:

$$|S_{21}|^2 = 10^{IL(\text{dB})/10}. \quad (4)$$

This transformation from dB to linear values is essential when performing network simulations, parametric studies, or when using analytical or neural network models that require linear S-parameters as inputs.

A short-response-time alternative for the full-wave parametric model based on the ANNs has been recently reported in [17]. As first step of building the parametric model, all the dimensions are kept constant, except the recess dimensions X and Y, which are further assumed to be equal ($X = Y$). A parametric model was developed to predict the device's return and insertion losses (S_{11} and S_{21} magnitudes expressed in dB) over 92–95 GHz. With the device layout fixed, beside the frequency, the recess dimension X (equal to Y) is treated as the sole input

parameter, varying from $15\ \mu\text{m}$ to $115\ \mu\text{m}$. Two separate multilayer neural networks, each with two hidden layers, model the frequency dependence of S_{11} and S_{21} , Fig. 2. The networks take frequency and X as inputs and output the corresponding S -parameter. The hidden neurons activation function is a log-sigmoid function, and the output neurons have linear transfer function. The ANN weights and biases are optimized using the Levenberg-Marquardt algorithm. The input and output data are normalized to $[-1, 1]$, which means that any input of the model is first to be preprocessed to $[-1, 1]$, and the outputs are to be postprocessed from the $[-1, 1]$ range to the original model parameter range, using the same normalization rules used in the model development procedures. Once trained, the ANNs provide fast and accurate predictions of the S -parameters across the considered range, making them suitable for switch design optimization.

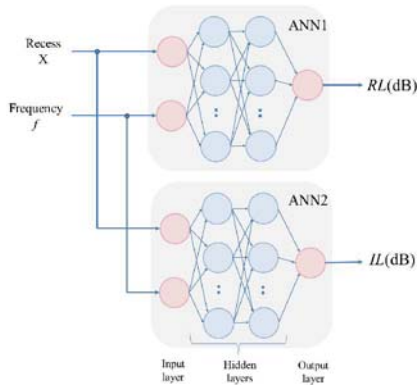


Fig. 2. Proposed model for the return and insertion losses versus recess dimension [17].

III. ANNs RESULTS AND DISCUSSION

3.1 Return Loss

The ANN trained to model the return loss (ANN1 in Fig. 2) has 15 neurons in the first hidden layer and 24 neurons in the second hidden layer. The blue markers in Fig. 3 present the frequency-dependent return loss plots from 92 to 95 GHz, for parameter X varying from 15 to $115\ \mu\text{m}$ with step $10\ \mu\text{m}$. The HFSS simulation results (circles) and ANN model predictions (dots) show excellent overlap across the W-band, confirming that the ANN can reliably predict return loss over the entire operational frequency range. Minor deviations at certain frequencies are negligible, suggesting that the ANN model is sufficiently accurate for design optimization and parametric studies, while drastically reducing computation time compared to full-wave simulations. The red testing points, for recess $X = 20, 50, 100\ \mu\text{m}$, respectively, closely follow the trend of the blue training predictions, demonstrating that the ANN generalizes well to unseen data.

Furthermore, frequency dependence of the S_{11} for different recess dimensions $X = 15\text{--}115\ \mu\text{m}$ with a step of $1\ \mu\text{m}$ is shown in Fig. 4. The results indicate that variations in the recess dimension have a pronounced effect on the

impedance matching of the switch across the W-band frequency range. It can be observed that there are some areas in the X input space where the return loss is staying almost unchanged with the change of the recess dimension.

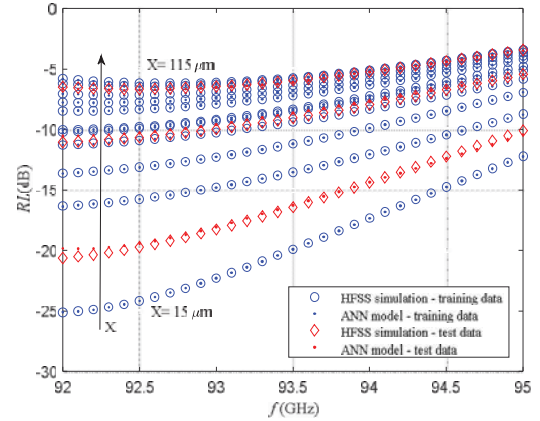


Fig. 3. Model prediction of return losses for different recess values. Training set – blue markers. Test set – red markers.

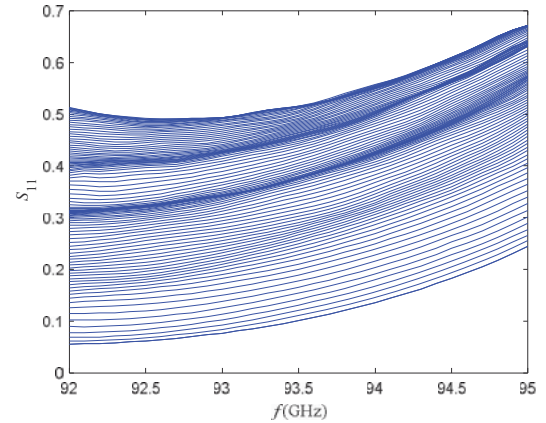


Fig. 4. S_{11} (linear value) as a function of frequency for different recess dimensions, $X = [15:115]\ \mu\text{m}$.

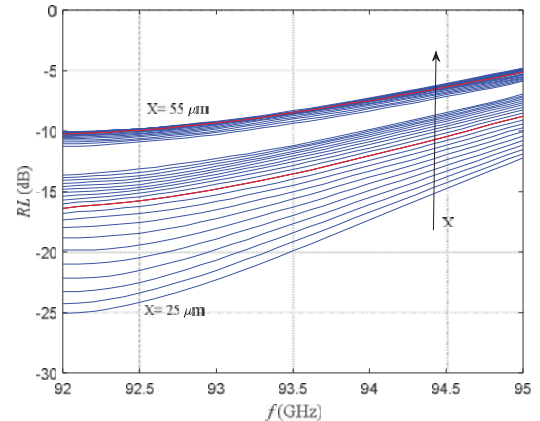


Fig. 5. Return loss as a function of frequency for recess dimensions, $X = 25$ and $55\ \mu\text{m}$, including max $\pm 10\ \mu\text{m}$ parametric variations (step of $1\ \mu\text{m}$).

The plots shown in Fig. 5 demonstrate the sensitivity of the return loss to small variations in the recess dimension. For both nominal recess values (red lines), $X = 25\ \mu\text{m}$ and $55\ \mu\text{m}$, changes of max $\pm 10\ \mu\text{m}$ lead to shifts in the

magnitude and frequency location of the return loss minima, indicating that fabrication tolerances can significantly affect impedance matching. The comparison between the two nominal recess dimensions further highlights differences in matching behavior across the W-band, emphasizing the importance of accurate recess dimension optimization in RF-MEMS switch design.

3.2 Insertion Loss

The ANN developed to model insertion loss (ANN2 in Fig. 2) has 10 neurons in the first hidden layer and 12 neurons in the second hidden layer. The plots in Fig. 6 show model prediction of insertion loss. Blue markers indicate the ANN predictions for the training dataset, while red markers represent testing results for several recess values $X = 20, 50, 100 \mu\text{m}$. HFSS simulation results are shown for comparison. The frequency-dependent IL plots (with the $10 \mu\text{m}$ recess dimension step) are displayed in the frequency range from 92 to 95 GHz, where the ANN predictions (dots) closely follow the HFSS simulation results (circles) throughout the W-band. This strong correlation indicates that the ANN model can accurately and efficiently estimate the insertion loss of the SiC-based RF-MEMS switch, offering a rapid alternative to full-wave simulations for design and parametric studies. The red testing points, not seen during the training, closely follow the trend of the blue training predictions, demonstrating that the ANN generalizes well to unseen data. Overall, this figure confirms that the ANN model can accurately predict insertion loss and reliably replace time-consuming HFSS simulations for both training and new geometrical cases.

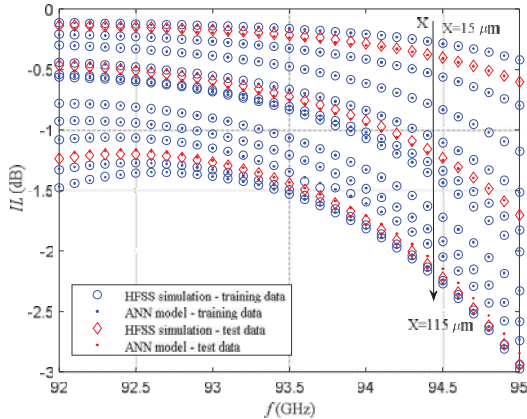


Fig. 6. Model prediction of insertion loss for training set (blue signs) and for the test with $X = 20, 50$ and $100 \mu\text{m}$ (red signs).

Moreover, the S_{21} linear value evaluated over the 92–95 GHz frequency range for recess values $X = 15\text{--}115 \mu\text{m}$ (step of $1 \mu\text{m}$) is shown in Fig. 7. The results indicate that variations in the recess dimension have a significant impact on the transmission characteristics of the switch across the W-band frequency range. In addition, the magnitude of the S_{21} varies with the recess dimension, suggesting that the optimal recess dimension for minimum insertion loss is frequency dependent.

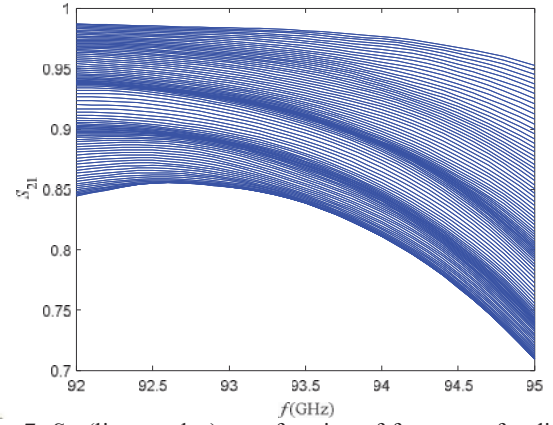


Fig. 7. S_{21} (linear value) as a function of frequency for different recess dimensions, $X = [15:1:115] \mu\text{m}$.

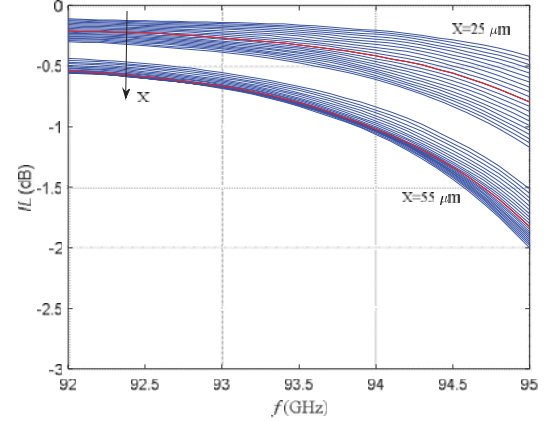


Fig. 8. Insertion loss as a function of frequency for different recess dimensions, $X = 25$ and $55 \mu\text{m}$, including max $\pm 10 \mu\text{m}$ parametric variations (step of $1 \mu\text{m}$).

Fig. 8 shows the insertion loss as a function of frequency for two nominal recess dimension values (red lines), $X = 25 \mu\text{m}$ and $X = 55 \mu\text{m}$, over the 92–95 GHz frequency range. For each nominal recess value (red curve), an additional parametric analysis is performed by varying the recess dimension by $\pm 10 \mu\text{m}$, resulting in twenty blue curves for each case. The results indicate that the insertion loss is sensitive to variations in the recess dimension, particularly at higher frequencies within the W-band and smaller values of recess X . Deviations of max $\pm 10 \mu\text{m}$ from the nominal values lead to observable changes in the magnitude of the insertion loss, reflecting variations in transmission efficiency and conductive and dielectric losses. The comparison between the two nominal recess dimensions reveals different loss characteristics, highlighting the trade-off between impedance matching and signal transmission. These results underscore the importance of precise control of the recess dimension for minimizing insertion loss and ensuring stable performance under fabrication tolerances.

The deviation from the IL nominal value for $X = 55 \mu\text{m}$ is depicted in Table I show that for this particular value, IL is more stable with the increase of X than with the decrease of it.

TABLE I
Deviations from the IL nominal value for $X = 55 \mu\text{m}$

$X (\mu\text{m})$	Maximum IL deviation (dB)	Average IL deviation (dB)
45	0.31	0.16
46	0.27	0.14
47	0.24	0.12
48	0.2	0.1
49	0.17	0.081
50	0.14	0.063
51	0.11	0.047
52	0.077	0.033
53	0.05	0.02
54	0.024	0.0092
55	0	0
56	0.022	0.0075
57	0.042	0.014
58	0.06	0.018
59	0.077	0.022
60	0.093	0.025
61	0.11	0.029
62	0.12	0.032
63	0.14	0.037
64	0.16	0.043
65	0.17	0.051

IV. POWER ANALYSIS DISCUSSION

In general, in the ON (closed) state, an RF-MEMS switch forms a low-resistance conductive path between the input and output transmission lines. When actuated, the MEMS bridge or cantilever makes metal contact (ohmic switch) or establishes the intended RF path, resulting in very low insertion loss, good impedance matching, and minimal reflected power. In this state, most of the incident RF power (typically 95–99%) is transmitted to the output, while only a small fraction is reflected due to residual mismatch and a small portion is dissipated as loss in the contact resistance, conductors, and substrate.

Furthermore, a power flow analysis of the analyzed RF-MEMS switch is performed here.

4.1 Relationships between Return/Insertion Loss and Power

Power flow of an RF device is shown in Fig. 9. Let the incident power at port 1 be P_{in} . This is the power that actually arrives at the DUT input.

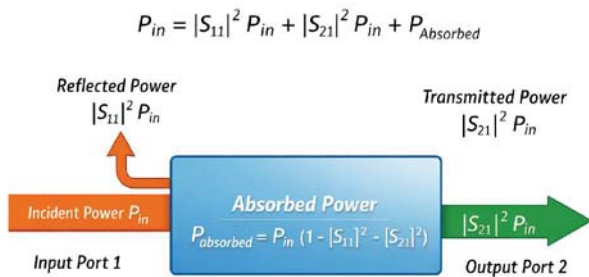


Fig. 9. Power flow of an RF device.

The power reflected back toward the source is determined by the reflection coefficient:

$$P_{reflected} = |S_{11}|^2 \cdot P_{in}, \quad (5)$$

i.e., in percents:

$$\%P_{reflected} = |S_{11}|^2 \cdot 100 \quad (6)$$

The power transmitted through the device to port 2 is determined by the transmission coefficient:

$$P_{transmitted} = |S_{21}|^2 \cdot P_{in}, \quad (7)$$

or in percents

$$\%P_{transmitted} = |S_{21}|^2 \cdot 100. \quad (8)$$

The power lost at port 2 is:

$$P_{absorbed} = P_{in} - P_{reflected} - P_{transmitted}, \quad (9)$$

as well as in percents:

$$\%P_{absorbed} = 100 - \%P_{reflected} - \%P_{transmitted}. \quad (10)$$

4.2 ON-State Power Flow Analysis

Fig. 10 presents the ON-state power distribution of the RF-MEMS switch over the 92–95 GHz frequency range, including reflected and transmitted power components derived from the simulated S -parameters of the analyzed switch.

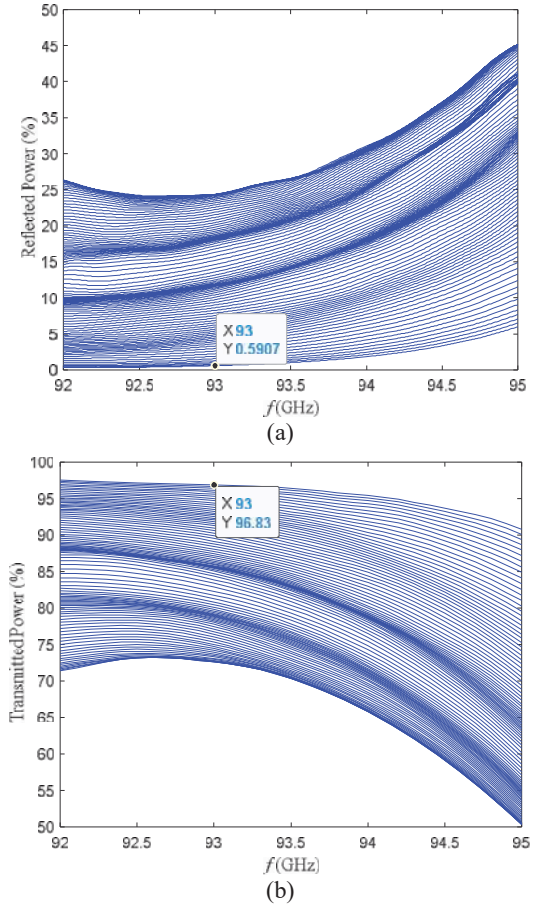


Fig. 10. ON-state power distribution of the RF-MEMS switch: (a) reflected power, and (b) transmitted power.

At lower frequencies, and for lower values of recess, the switch exhibits high transmission efficiency (Fig. 10b), with transmitted power exceeding approximately 95–97%, indicating low insertion loss and good impedance matching in the closed state. As frequency increases, as well as recess dimension, the transmitted power decreases to about 50–70%, primarily due to increased conductor loss and parasitic effects inherent to millimeter-wave operation.

The reflected power (Fig. 10a) increases with frequency, rising from approximately 0–27% at 92 GHz to nearly 45% at 95 GHz, revealing a gradual degradation in impedance matching caused by structural discontinuities and parasitic reactances. Certain recess values yield lower return loss, indicating improved matching and reduced reflected power.

Moreover, an example of power levels is shown in Fig. 10. At 93 GHz with a recess value of $X = 15 \mu\text{m}$, the structure demonstrates excellent performance, transmitting 96.83% of the input power with minimal reflection (0.59%) and low absorption (2.58%).

V. CONCLUSION

This paper presents an ANN-assisted analysis of a W-band RF-MEMS switch. While the device is not optimized for performance, the focus is on demonstrating how artificial neural networks can be used to model and predict the return loss and insertion loss over 92–95 GHz. Using the switch recess dimension as the primary input, separate ANNs capture the frequency-dependent S-parameters, providing a fast and accurate model for analyzing the scattering parameters (i.e. return and insertion losses), as well as power flow.

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