Design and Optimization of a Near-Field Measurement Probe for a Minimized Scattering Cross Section

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***Abstract* — This paper studies the relation between the mono-static scattering cross section (SCS) of a near-field measurement probe and its antenna capabilities, e.g. the return loss (S11), radiation pattern and peak gain. For this purpose, a highly parameterized model is created and several simulations are conducted with a rectangular open ended waveguide (OEWG), to assess the effects of polarization and geometry. Different techniques are used to reduce the SCS, while maintaining a high antenna performance. The first one is to reduce the aperture of the antenna, by reducing the taper opening of the OEWG. Furthermore, the effects of dielectric loading and adding absorber material around the OEWG are analyzed. The employed techniques are assessed based on their capability to reduce the SCS of the measurement probe, while maintaining the antenna performance. It is shown, that the polarization is significantly more important than geometrical variations with differences between 3 to 15 dBsm for co-polar and cross-polar cases. An SCS reduction of around 10 dBsm can be achieved, by combining the different techniques, employed in this paper. The advantages and disadvantages of these techniques are described and a guideline to reduce the SCS of OEWGs is presented.**

***Keywords* — measurement probe, near-field, rectangular waveguide, scattering cross section.**

I. Introduction

Several different technologies are key to the success and prominence of fifth generation (5G) communications. One of the enabling technologies for 5G are multiple input multiple output systems, leading to a continuously rising usage of antenna arrays [1]. Therefore, accurate measurements of antenna arrays and especially the capability to measure single array elements is key to ensure a proper communication system [2]. In order to acquire high quality and accurate measurements, a low SCS is required, reducing the impact of the measurement probe on the antenna under test [3].

A multitude of different studies has been conducted to reduce the SCS of measurement probes for different application areas [4], [5]. Das et al. [4] utilized a periodic structure superstrate with varactor diodes to reduce the antenna SCS, while maintaining the antenna performance. Liu et al. [5] created a low SCS antenna array with reconfigurable scattering patterns by using digital antenna units with pin diodes, such that the scattering pattern can be tuned to a desired direction.

However, most of these studies are optimizing a measurement probe for a specific use case. Research to reduce the SCS of antennas in general is rare [6], [7]. Ko et al. [6] gives an insight into the effects of chamfering for OEWGs and their influence on the SCS. Chamfered rectangular OEWGs have a lower mono-static SCS in the boresight direction. This effect is increasing for higher frequencies. Newell et al. [7] evaluates the SCS effects of absorbers, which are used to cover the mounting structures behind an antenna. Some configurations lead to significant pattern distortions for the probe. Therefore, general guidelines are presented to reduce the effect of absorbers on the antenna pattern and gain.

This paper aims to derive similar rules for designing and optimizing OEWGs to obtain a minimized mono-static SCS. OEWGs are chosen, since they are a widely used class of near-field probes. They are inexpensive and can be used for a wide range of measurement applications. Furthermore, the mono-static SCS is analyzed in this paper, which is more difficult to assess than the bi-static SCS. Each result is computed separately for every analyzed angle, leading to a significantly higher computational complexity for electromagnetic solvers. In this context, the effect of three different SCS improvement techniques is evaluated; reducing the aperture size by adapting the taper opening of an OEWG, adding absorbers around the OEWG and dielectric loading of the waveguide. The evaluation is done by comparing the SCS reduction to the respective antenna performance degradation.

The remainder of this paper is structured as follows. Section II describes the three SCS reduction techniques and illustrates the conducted simulations. Section III shows the results and evaluates them. Finally, Section IV concludes the paper and gives an outlook for future research.

II. Methodolody

The software simulation tool Empire XPU is utilized for all conducted simulations in this paper. It is an EM solver using the finite difference time domain method. The validity of the measurement probe and mono-static SCS simulations are verified, by utilizing known use cases, e.g. the SCS of a sphere or corner reflector and comparing them with their analytical results as well as results from the simulation software Feko.

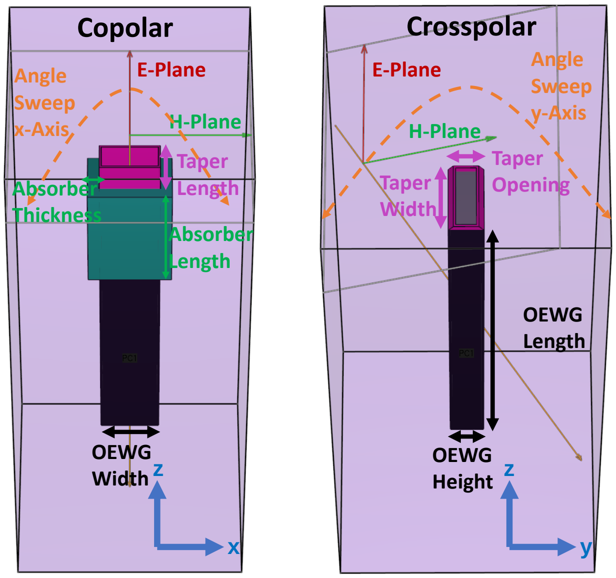


Fig. 1. The waveguide (black) on the left depicts the co-polar case, with the original taper (pink) and with absorbers (green). The OEWG is in the z-x plane and an angle sweep over the x axis is performed. The waveguide on the right shows the cross-polar case with a shortened and reduced opening taper without absorbers. This perspective is from the z-y axis and essentially rotates the waveguide by 90°. The angle sweep is performed over the y axis, thus creating a cross-polar scenario. The green arrow for the incident wave in the figure shows the H plane, while the red arrow indicates the E plane.

Fig. 1 shows two different mono-static SCS measurement setups for the waveguide, the co-polar case on the left and the cross-polar case on the right. Furthermore, there is also a third constellation with a mixed polarization for the incident wave, which is essentially in between the two depicted states, with a 45° rotation difference from the co-polar and cross-polar case. This paper includes all results from these three constellations. Furthermore, the SCS is calculated for different angles, e.g. at 30°, 20° or the boresight direction. The exact sweep direction is depicted by the orange dashed arrows and is always done for the respective plane of the waveguide. The coordinate systems are depicted at the bottom of the two constellations and show the angular sweep for the x axis on the left and for the y axis on the right side of Fig. 1. The total angular range is chosen between 0° to 35° in 5° steps for each of the three cases.

For the antenna performance of the measurement probe, the S11, radiation pattern and peak gain are evaluated. By comparing the degradation of these parameters to the SCS improvement, we can obtain the effectiveness of the SCS reduction techniques. The taper at the end of the OEWG is used to adapt the length and opening, reducing the aperture size and decreasing the SCS of the OEWG. Additionally, absorbers are added, to reduce the scattering effects around the OEWG, as illustrated in Fig. 1. Finally, a dielectric loading is performed for the waveguide and taper, leading to smaller dimensions, scaling with the square root of the permittivity of the chosen dielectric. This reduction in size is once again improving the SCS performance of the measurement probe.

The frequency band of the rectangular OEWG ranges from 4.8 to 5.0 GHz and all results presented in this paper are taken at the center frequency of 4.9 GHz. This range is chosen, since our basestations are operating at these frequencies and should be measured as accurately as possible, minimizing the effects from the measurement probe. Any significant deviations of the results across the frequency band will be mentioned during the evaluation. Also, the measurement units and all adaptations of the OEWG will be given as multiples of the corresponding wavelength or as a percentage of the original size, generalizing the results from this paper for all OEWGs.

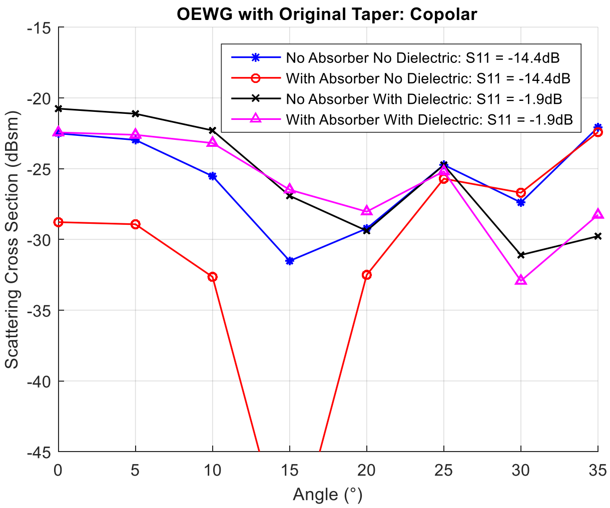
The length, width, height and wall thickness of the waveguide are 4.92λ, 0.78λ, 0.36λ and 0.03λ respectively, while $\lambda = 61.18$ mm. Three different variations are utilized for the taper. The original taper is depicted in the left part of Fig. 1 and has a taper width of 0.78 λ, a taper length of 0.33 λ and a taper opening of 0.41 λ. The taper on the right in Fig. 1 is shortened to 25% of the original length and has a reduced taper opening of 60% compared to the original one. Therefore, this taper is labeled as the 25,60% taper. The final taper variation has the same dimensions as the original one, except for the taper opening, which is reduced to 70% of the original, thus labeled as the 70% taper. Furthermore, the absorber is defined with an absorption of 2 dB/mm, a thickness of 10 mm and a length of 100 mm. The position is at the end of the OEWG and stops exactly when the taper starts. The dielectric was chosen to be polylactic acid (PLA), since it is used for 3D printing applications, enabling an easy manufacturing of the measurement probe. It has a permittivity of $\epsilon = 2.85$ and a loss tangent of $tan(\delta) = 0.0035$ [8].

III. Results

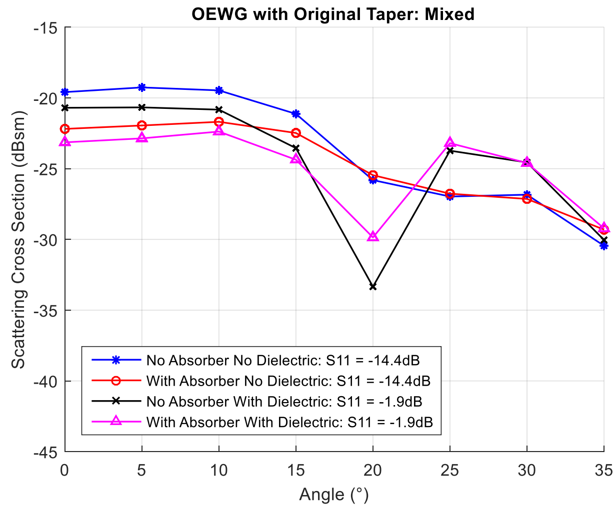
All SCS results for the waveguide with the original taper are depicted in Fig. 2. It can be seen, that the polarization has the biggest effect on the SCS performance. Furthermore, some angles and frequencies lead to a resonance behavior, significantly reducing the SCS of the measurement probe, e.g. in Fig. 2a. In general, absorbers around the OEWG lead to a better SCS performance of around 1 to 10 dBsm, while having negligible effects on the antenna performance. The S11 and peak gain changes are around 1% for most cases, while there are no significant changes for the radiation pattern. However, applying a taper with a reduced opening or dielectric loading has a significant impact on the antenna performance, as depicted in Table 1 and Table 2 for the original tapered OEWG without absorbers. The differences of the S11, peak gain and radiation pattern are directly correlated with each other, while the changes are most visible for the S11 parameter. The other metrics, in this case the peak gain and especially radiation pattern, do not change as significantly as the S11, thus the S11 value is mostly shown in this paper.

Table 1. S11 for different taper openings without absorbers and dielectrics.

Open. (λ)	.07	.11	.14	.18	.22	.25	.29	.32	.36
Taper (%)	20	30	40	50	60	70	80	90	100
|S11| (dB)	1.6	2.3	3.3	4.4	5.7	7.7	9.4	11.6	14.4



(a)



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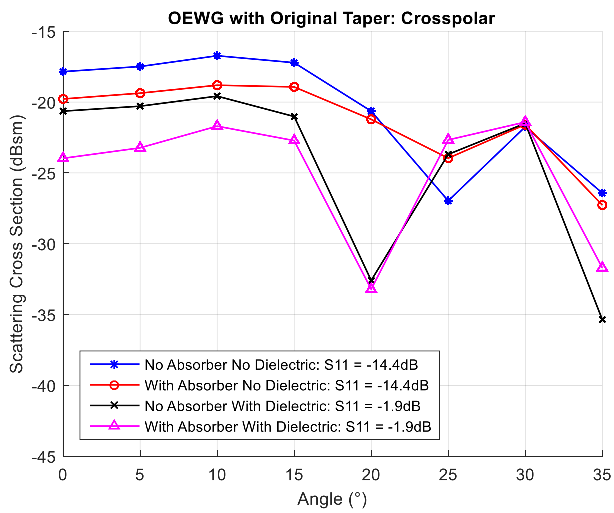

(c)

Fig. 2. These figures show the results for all 3 polarizations of the original tapered OEWG, utilizing different techniques, e.g. absorbers, dielectric loading, none of the both or both at the same time, to improve the SCS of the measurement probe. The corresponding S11 values are depicted in the legend.

Table 2. S11 of the original taper OEWG using dielectr. loading, no absorbers.

Dielectric Permittivity (ϵ)	1	1.5	2	2.5	3	3.5	4	4.5
|S11| (dB)	14.4	14.1	10.3	4.1	1.4	0.5	0.2	0.1

Fig. 3 shows the SCS results of the OEWG with the 70% taper on the left and the 25,60% taper on the right. Both of these probes have a better SCS performance, than the original tapered OEWG. However, the antenna performance is also significantly lower, with an S11 of -7.7 dB and -8.6 dB for the 70% and 25,60% taper respectively. The peak gain was reduced from 7 dBi of the original tapered OEWG to 6.25 dBi for the 70% and 6.5 dBi for the 25,60% taper respectively. So a tradeoff between antenna and SCS performance has to be made. Furthermore, a reduction of the S11 can be seen in Fig. 3b, 3d and 3f, when applying absorbers around the waveguide. This is due to the shorter taper length of the 25,60% taper. So the antenna performance is affected by the absorbers when they are too close to the aperture of the OEWG.

Another important point is the fact, that the dielectric loading of the OEWG in the co-polar cases leads to a worse SCS behavior, than only applying absorbers around the waveguide. This can be seen in Fig. 2a, 3a and 3b for all taper variations. The reason for this is the resonance behavior of the waveguide, which is optimized for co-polar waves, transmitting and receiving them without any significant losses. However, applying a dielectric loading leads to a worse S11 and thus antenna performance. Therefore, this resonance behavior of the OEWG is disturbed and the incoming waves are mostly reflected back now, compared to the waveguide without dielectric loading. So for smaller angles, e.g. below 25° as it can be seen from Fig. 2a, 3a and 3b, this resonance behavior is maintained, leading to the lowest SCS values. However, increasing the incident angle of the incoming waves

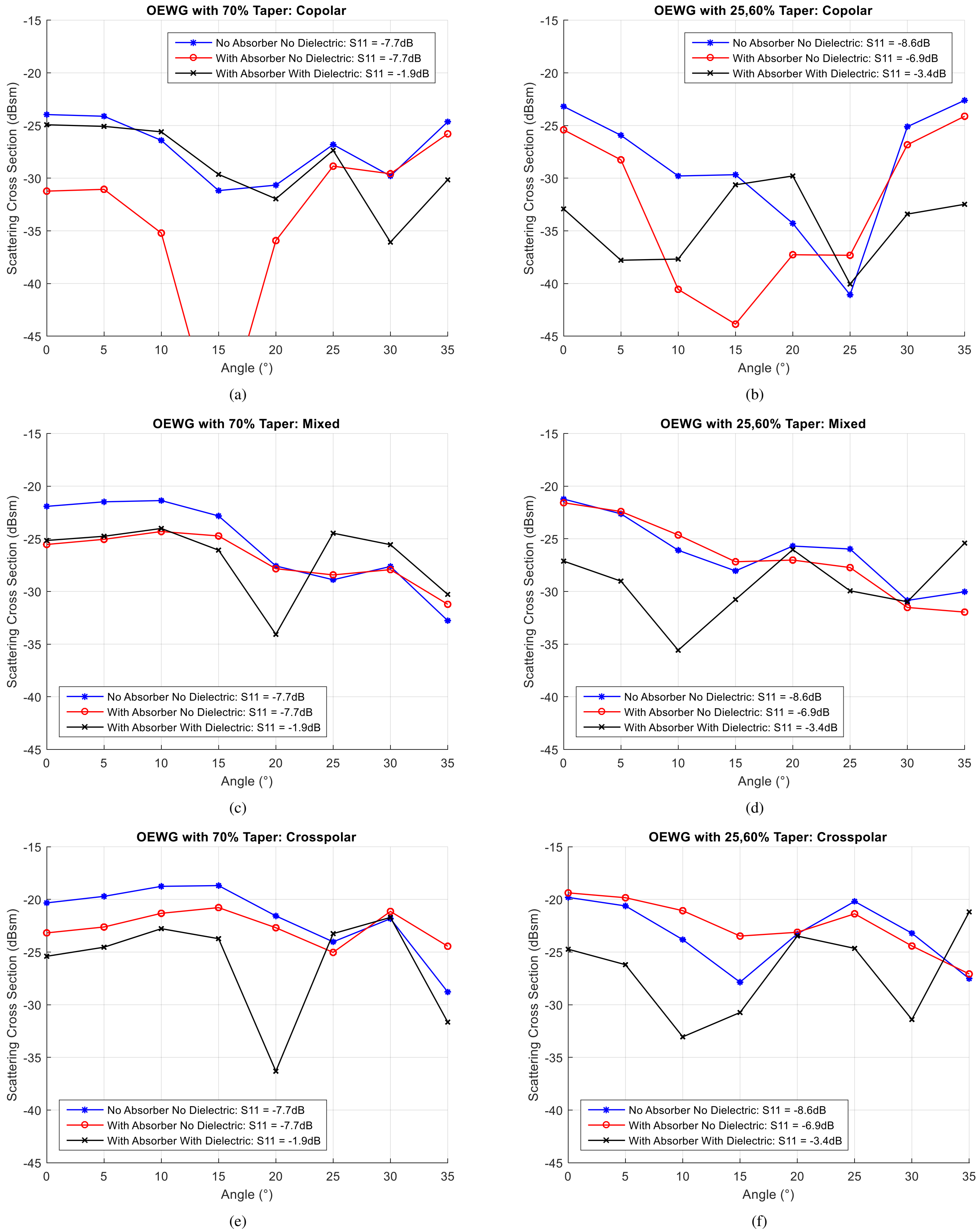

Fig. 3. The figures on the left, Fig. 3a, 3c, 3e, show the results of the different polarizations for the 70% taper, while the figures on the right, Fig. 3b, 3d, 3f use the 25,60% taper. The OEWG without any modifications, with absorbers and with absorbers as well as dielectric loading are shown. The S11 for each of these case is depicted in the legend.

above this angle nullifies the advantage from the antenna performance. Therefore, the results are inverted from that angle onwards and the low loss and low reflective behavior of the measurement probe can no longer be utilized, leading to the best SCS performance for higher angles.

However, this behavior is unique for the co-polar scenarios and applying absorbers as well as dielectric loading to the waveguide provides the best SCS performance in general, as it can be seen in Fig. 3. However, they also lead to a significant degradation for the S11 with -1.88 dB and -3.44 dB. The difference in antenna performance for these waveguides is due to their different tapers. The 25,60% taper leads to a better transition between air and dielectric and thus a better impedance matching. So even though the S11 of the 25,60% taper was lower than that of the 70% taper before the dielectric loading, as it can be seen from the difference of the S11 between the right and left side of Fig. 3, it gets better afterwards due to the improved transition. Therefore, the antenna performance can be significantly increased by constructing a good air to dielectric transition.

To summarize, adding absorbers around a waveguide leads to SCS improvements of 1 to 10 dBsm without affecting the antenna performance, as long as the absorbers maintain a distance of at least 0.2λ to the aperture. For further improvements, a tapering and additionally a dielectric loading can be used. These techniques improve the SCS performance by another 1 to 10 dBsm respectively. However, there will be reductions in the antenna performance without further optimization, especially for the dielectric loading. So selecting a suitable taper for the permittivity of the utilized dielectric is key and the design of the taper and dielectric should be done in parallel to ensure a proper transition between air and dielectric.

IV. Conclusion

Three different techniques to reduce the mono-static SCS of OEWG measurement probes are analyzed in this paper. First, an aperture reduction by adapting the taper of the OEWG is analyzed. Furthermore, the addition of absorbers and the effects of dielectric loading are analyzed. It is shown, that the polarization of the antenna is the most important parameter for the SCS performance, providing differences between 3 to 15 dBsm. Adding absorbers around the OEWG does not provide any significant drawbacks, as long as a reasonable distance of at least 0.2λ is maintained to the aperture. The taper and dielectric loading should be designed in parallel to provide the best possible air to dielectric transition and thus best antenna performance. Applying these techniques provides an increase of up to 15 dBsm for the mono-static SCS of an OEWG measurement probe, which can also be generalized for all OEWG measurement probes, as long as the dimensions are scaled according to the wavelength of the application.

In the future, the knowledge of the relation between tapers and dielectric loading can be improved, by adding custom made air to dielectric transitions for different tapers and dielectric permittivities, optimizing the antenna performance even further.

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