# Dielectric Characterization and Optimization of Wide-band, Cavity-Backed Spiral Antennas

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***Abstract*** **—** This paper presents a novel approach to facilitate the design of wideband, cavity-backed spiral antennas. Using this approach, first, a 2-18 GHz, two-arm cavity backed Archimedean spiral antenna has been designed in FEKO. A multilayer dielectric absorber has been introduced in the cavity to facilitate unidirectional operation of the antenna. In order to incorporate the frequency-dependent complex permittivity data of the absorbing materials inserted in the cavity, precise microwave instrumentation has been used to determine these parameters experimentally. Based on this data, a genetic algorithm optimization procedure has been applied to derive the most favorable geometry of the absorbing cavity. Our results show that a design thus optimized significantly improves key performance parameters, maximizes the co-polarized gain, and minimizes the cross-polarized gain of the antenna across its operational bandwidth. We have then extended the approach to the design of a zigzagged 2-arm Archimedean spiral antenna and also a 1.5:1 ratio elliptical spiral antenna and presented the radiation characteristics here.

***Index Terms*** **—** Axial ratio, broadband absorbing materials, cavity-backed spiral antenna, complex permittivity measurements, genetic algorithm optimization, radiation patterns.

## I. INTRODUCTION

Spiral antennas with their wide bandwidth have always been a fascinating topic. In recent years, system performance demands on these antennas are becoming more and more complex. Currently, considerable interest has been placed on developing cavity-backed spiral antennas that retain their bandwidth performance despite having frequency-dependent lossy materials added to their cavities [1]. Among these antennas, the Archimedean spiral antennas are one of the most popular ones that exhibit exceptionally large bandwidths, can easily be spatially deployed and have the ability to maintain near-circular polarization and consistent input impedance over their bandwidth of operation [2].

The Archimedean spiral antenna is entirely specified by its angles as opposed to its physical length. It is a frequency self-selecting structure, in the sense that it radiates from a region where the length of the arm approximately equals to one or integer multiples of the wavelength. This gives rise to its broadband or frequency independent nature. The antenna has front-to-back symmetry and radiates bi-directionally [3]. But in most cases, a unidirectional pattern is preferred to detect reflections from or transmit towards one direction only. Therefore, a metallic cavity is added to absorb the back wave completely. Now, a cavity of depth $\lambda/4$ would absorb the back wave through destructive interference. But this condition would be satisfied for one frequency only, and we would obtain absorption for a very narrowband. Hence, it becomes necessary to insert absorbing materials in the cavity that can effectively absorb EM energy over a wide range of desired frequencies.

One common approach to extending the bandwidth of microwave absorbers is by using multiple layers of dielectric materials. The effective impedance in the material is gradually tapered with distance to minimize reflections. The loss mechanisms of absorbing materials are captured in the complex dielectric permittivity and magnetic permeability of that material. These properties are functions of frequency and consequently the absorbing properties vary significantly as the frequency of operation changes.

The optimum approach for the design of such an absorber would be to determine analytically the required permittivity and permeability values as a function of distance into the material, so that the reflection coefficient is minimized over a given frequency range, subject to incidence angle and thickness constraints. Unfortunately, the general form of the problem has not been solved yet [4]. What is done in practice is that the absorption properties of known materials are measured experimentally, and then different layers of dielectric materials are stacked together through a trial and error process. The effectiveness of these multi-layer absorbers is again determined from empirical data. This process is further complicated by the requirement of precise and sophisticated microwave techniques and instrumentation for high frequency characterization of dielectric materials.

An ideal broadband absorber should not only have the desired frequency coverage, but should also be sufficiently light, thin, inexpensive, and durable. Commercial absorbers are available only in certain dimensions, fixed by the manufacturers. The absorption characteristics vary significantly with material thickness, making the material dimensions an important parameter. It is very difficult to physically measure the absorber behavior for varying thickness values over a wide range of frequencies. The most feasible option would be to use optimization algorithms such that for a given set of materials, we obtain the best possible dimensions.

Keeping all this in mind, the design and analysis of a cavity backed spiral antenna entails the modeling of the antenna using proper simulation tools, appropriate characterization of the material constitutive properties and optimization of the dimensions of the stacked absorbing layers, so that the most favorable balance among bandwidth, thickness, and weight constraints of inserted materials and gain characteristics of the antenna is obtained.

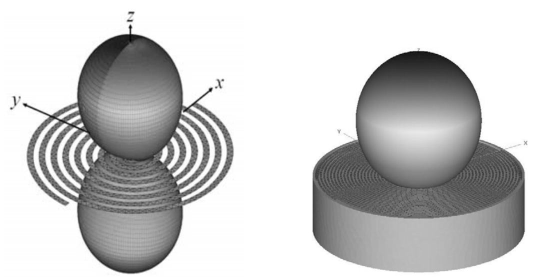
Here, we have modeled a two-arm, cavity-backed, Archimedean circular spiral antenna with a multi-layer AN-74 dielectric absorber inserted in the cavity. The antenna has been simulated for its radiation characteristics over the frequency range 2 -18 GHz first without the absorbing materials, then with absorbing materials of fixed non-optimized thicknesses, and finally with optimized thicknesses for each absorbing layer. To capture the frequency dependent complex permittivity and loss tangent data for each layer, we used a network analyzer based transmission-reflection method in the High Frequency Materials Measurement and Information Laboratory at Tufts University. The material dielectric properties thus obtained were used in EM simulation software FEKO [5] to define the absorber material properties. With the FEKO optimizer, we then determined the optimal thickness of each layer such that the absorption properties are sufficiently retained, co-pol RHCP gain maximized and cross-pol LHCP gain minimized over the entire bandwidth.

The radiation patterns were then compared for their broadband performance. Our results show that we have been able to obtain an improved design with the best possible radiation characteristics when the knowledge of frequency-dependent data was accurately applied to the EM solver. The concept can be successfully extended to the design of any wideband antenna in general. We are motivated to investigate a wide range of dielectric and magnetic absorbing materials and design the most accurately characterized broadband antennas prior to their fabrication. We have then extended the approach to the design of a zigzagged 2-arm Archimedean spiral antenna and also a 1.5:1 ratio elliptical spiral antenna and presented the radiation characteristics here. Figure 1 shows the general antenna layout and direction of radiation for Archimedean spiral antennas.

Figure 2 shows a zigzagged Archimedean spiral and an elliptical Archimedean spiral antenna.

## II. DIELECTRIC CHARACTERIZATION OF BROADBAND ABSORBERS

A 3-layer composite dielectric absorber, AN 74, manufactured by Emerson and Cuming, was used for the absorbing cavity. Each layer is a carbon-loaded polyurethane foam absorber which typically provides -20 dB insertion loss at different frequency bands from 2-18 GHz.




(a) (b)

Fig. 1. a) Bidirectional radiation pattern of a two arm Archimedean spiral antenna, b) unidirectional radiation pattern of a cavity-backed, two-arm Archimedean spiral antenna.

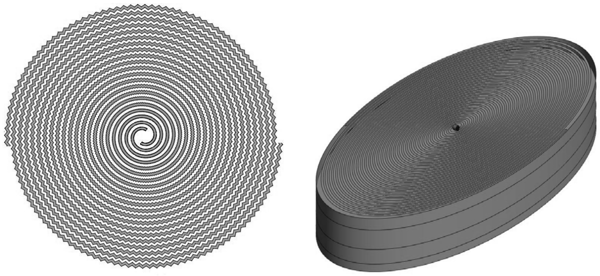


Fig. 2. a) Zigzagged 2-arm Archimedean spiral antenna, b) elliptical two-arm Archimedean spiral antenna.

The complex dielectric permittivity $\varepsilon_r$ of each layer of the AN-74 absorber was accurately characterized with an Agilent Vector Network Analyzer using a waveguide-based transmission-reflection method.

The network analyzer automatically measured the complex reflection coefficients and transmission coefficients that resulted when a sample of material was inserted in a waveguide. The network analyzer measured the scattering parameters $S_{11}$ and $S_{21}$. Once these coefficients were known, the values of $\varepsilon_r$ were then calculated using the Jarvis-Baker method [6] for each of the three layers of the absorber. Data is obtained by performing measurements at 201 equally spaced frequency points. The data is stored, and the complex permittivity and permeability of the composite materials are calculated from the measured s-parameters using a MATLAB [7] program based on the Weir algorithm [8].

We denoted the three layers of the composite absorber as hard, middle, and soft layer, with the soft layer being closest to the antenna and the hard layer attached to the metallic cavity. For maximum absorption, there should be no mismatch between the absorber and air. In order to reduce mismatch, the EM wave should see impedance close to 377 ohm when it crosses the air-absorber interface. From the data we obtained from our measurements, we found that the soft layer provides the closest match in terms of impedance seen by the incident wave. Thus, we placed this layer closest to the antenna followed by the middle layer and hard layer.

The frequency dependent permittivity values are shown in Fig. 3.

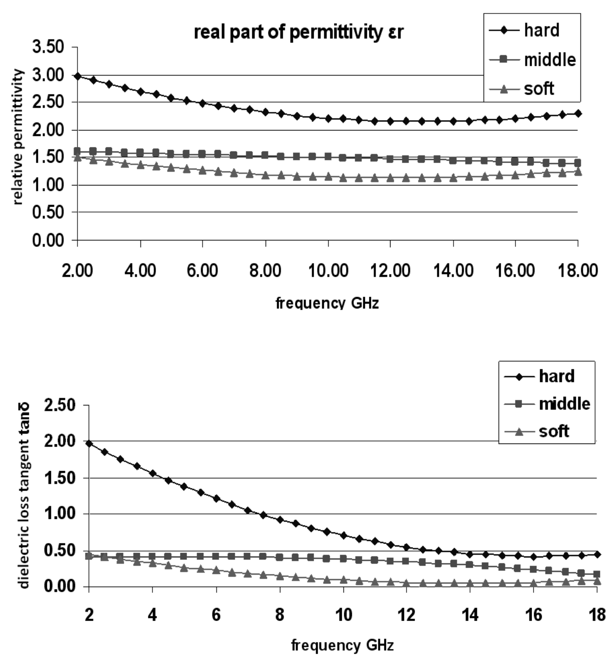



Fig. 3. Real part of permittivity and loss tangent for three layers of the composite absorber.

From the experimental values, we used curve fitting methods to derive the following equations relating complex permittivity to frequency.

***Permittivity and loss tangent equations*:**

***Hard:*** $\varepsilon = .0065f^2 - 0.1723f + 3.281$ (1)

$\tan\delta = 0.0078f^2 - 0.2514f + 2.4373$ (2)

***Middle:*** $\varepsilon = -6e\text{-}17\ f^2 - 0.0133f + 1.6283$ (3)

$\tan\delta = -0.0015f^2 + 0.0147f + 0.38$ (4)

***Soft:*** $\varepsilon = 0.0036\ f^2 - 0.0872f + 1.659$ (5)

$\tan\delta = 0.0027f^2 - 0.0763f + 0.5838$ (6)

Thus, by using very precise microwave measurement techniques, we were able to obtain permittivity data for each layer of the composite absorber from 2 to 18 GHz.

## III. OPTIMIZATION OF WIDEBAND ANTENNAS

Derivation of frequency dependent parameters of the absorbing materials greatly facilitates designing optimum dimensions of the lossy cavity. Once we have the equations relating permittivity to frequency, it then becomes straightforward to use this data to define material properties in any electromagnetic simulation software with an optimizer feature available. The antenna can then be simulated at all frequencies for their radiation patterns by varying the material thicknesses. With optimization of the absorber dimensions, it becomes possible to obtain wider bandwidth and lower reflectivity. Although it is possible to calculate the reflectivity of a multilayer absorber, it is unfeasible to analytically solve for the optimum thickness of each layer over a wide range of frequencies. Fortunately, computer-based numerical algorithms can efficiently handle such complicated calculations. The FEKO simulator offers a number of numerical techniques to optimize the physical parameters of a design. Since a major point of concern for most algorithms is that they converge to local optima, we chose a global optimization technique, i.e. the genetic algorithm for our purposes if deriving the most favorable geometry of the composite absorber [5].

Multiple objectives were defined in this procedure to improve the overall radiation pattern of the antenna. Due to time and memory constraints, the number of maximum iterations was set to 80. We also incorporated the frequency dependent permittivity relations directly in the EDITFEKO solution settings. This allowed for the material properties to be appropriately updated as the frequency was varied during one complete iteration of the optimizer. Based on the computed electromagnetic parameters, we proceeded to optimize the thickness of each layer and depth of the cavity such that the RHCP gain of the spiral was maximized, LHCP gain minimized, reflection from the absorbing layers minimized, and absorption properties of the lossy composite material sufficiently retained over the entire bandwidth of operation.

We used the computed permittivity values in the FEKO software optimizer utility to arrive at the best possible thickness values that work best for an Archimedean spiral. For a 2-18 GHz spiral, a minimum composite absorber thickness of 0.805 inches and a 0.178 inch air gap between the antenna and absorbing layers gave the best broadband co-pol gain and axial ratio performance. We also simulated the antenna and observed the gain characteristics using industry specified absorber dimensions and also with no absorber inserted in the cavity at all. These results will serve as a reference to analyze how much improvement has been achieved through optimization. The generalized industry specified thicknesses are adequate for material testing purposes. However, in our work, we arrived at optimum absorber dimensions that provide the best radiation performance of an antenna model. In this way, prior to fabrication of the designed antenna, the required optimum dimensions can be specified to an absorber manufacturer, and each layer of the composite structure can be tailored to the needs of a specific application. In this way, we can eliminate the necessity of using adhesives to increase the thickness or further machining of the layers to decrease the thickness to a certain value.

Our contention is that this procedure can be used to design wideband antennas of any structure and cavity configuration.

## IV. RESULTS AND DISCUSSION

The model was simulated at 9 discrete frequency points at intervals of 2 GHz. Upon completion of the optimization process, the final optimum thicknesses for the hard, middle, and soft surfaces were 0.257, 0.229, and 0.319 inches, respectively. Industry specified non-optimized thicknesses for each absorbing layer was 0.25 inches for each layer. The optimized absorber dimensions showed significant improvement over the non-optimized model.

### A. Gain

A comparison of the boresight gains for the principle plane φ=0 of the antenna is shown in Table 1. It can be observed that throughout the operational band, the optimized spiral demonstrates sufficiently high gains, low side lobes, and no splits in the main beam for the entire frequency range of interest. It is also evident from the table that the introduction of the absorber layers in the cavity gave better isolation and optimization allowed for more consistent gain values throughout the bandwidth.

Table 1: Co-pol and cross-pol gain of optimized and non-optimized antenna

| Freq (GHz) | Boresight Gain (dB) | | | | | |
|---|---|---|---|---|---|---|
| | no absorber inserted in cavity | | absorber layers of equal thickness | | absorber layers of optimal thickness | |
| | RHC | LHC | RHC | LHC | RHC | LHC |
| 2 | -0.10 | -3.53 | -0.13 | -19.13 | 2.33 | -9.74 |
| 4 | 4.18 | -5.63 | 3.66 | -15.56 | 4.67 | -14.42 |
| 6 | 6.00 | -14.73 | 5.94 | -40.20 | 5.04 | -62.19 |
| 8 | 5.44 | -21.33 | 6.49 | -64.20 | 5.94 | -60.75 |
| 10 | 7.12 | -29.32 | 5.25 | -63.69 | 5.04 | -71.20 |
| 12 | 2.49 | -54.56 | 5.22 | -49.57 | 5.94 | -58.41 |
| 14 | 5.02 | -47.97 | 5.04 | -49.94 | 5.76 | -72.46 |
| 16 | 0.90 | -52.32 | 5.21 | -54.38 | 6.12 | -56.96 |
| 18 | 4.60 | -45.45 | 6.29 | -45.06 | 6.30 | -45.25 |

### B. Axial ratio

Figure 4 shows the axial ratio for all three configurations on boresight. An axial ratio close to 0dB implies that circular polarization is being maintained. The antenna without an absorber loaded cavity showed large values for axial ratio for frequencies until 7GHz. With the absorber inserted in the cavity, axial ratio was fairly less than 4 dB and in most cases, close to 0dB across the entire band. It is evident that the purity of circular polarization was sufficiently retained.

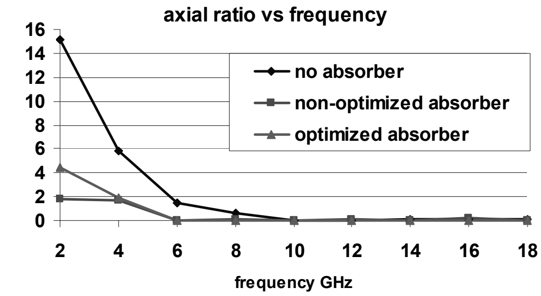



Fig. 4. Variation of axial ratio of the spiral antenna with frequency.

### C. Return loss

Figure 5 gives a comparison of the return loss $S_{11}$. In the absence of absorbing layers, the return loss was as high as -3dB throughout the band of operation. Return loss is efficiently minimized to acceptable levels by loading the cavity with multi-layer absorbing materials.

In defining the optimization objectives, we did not attribute equal weights to all optimization goals. For instance, more weight was given to gain performance across the bandwidth than axial ratio and front-end reflection. As a result, the gain performance shows relatively greater improvement than axial ratio or reflection coefficient. Depending on the application, it is always possible to optimize for certain radiation characteristics or specific bandwidths of interest, where maximum performance is desirable.

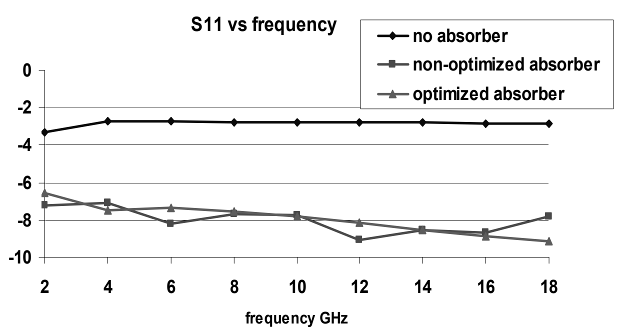



Fig. 5. Variation of return loss of the spiral antenna with frequency.

## V. EXTENSION OF DESIGN TO OTHER SPIRAL MODELS

### A. Cavity-backed zigzag Archimedean spiral

To reduce the size of the antenna, zigzag shaped arms can be used, so that the same length now occurs in a region much closer to the center of the spiral. But a zigzag circular spiral compromises the gain of the antenna compared to the simple circular spiral [9].

### i. Gain

The boresight gains for both principle planes of the optimized antenna are shown in Table 2.

### ii. Axial ratio

Figure 6 shows the axial ratio on boresight. Axial ratio was fairly less than 3.5dB and in most cases, close to 0 across the entire band. It is evident that the purity of circular polarization was sufficiently retained.

Table 2: Co-pol and cross-pol gain of optimized zigzag antenna

| Freq (GHz) | Gain (Φ=0° plane) | | Gain (Φ=90° plane) | |
|---|---|---|---|---|
| | RHC | LHC | RHC | LHC |
| 2 | 2.32 | -7.48 | 2.30 | -7.48 |
| 4 | 5.02 | -13.83 | 5.02 | -14.22 |
| 6 | 5.36 | -53.78 | 5.36 | -53.78 |
| 8 | 5.42 | -48.58 | 5.42 | -48.58 |
| 10 | 5.56 | -50.10 | 5.56 | -50.10 |
| 12 | 5.69 | -43.79 | 5.69 | -43.79 |
| 14 | 5.96 | -40.76 | 5.96 | -40.65 |
| 16 | 6.22 | -52.85 | 6.22 | -52.85 |
| 18 | 6.35 | -54.97 | 6.35 | -54.97 |

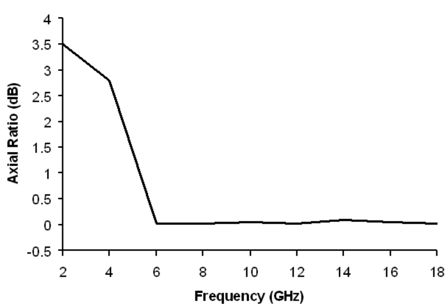



Fig. 6. Variation of axial ratio of the zigzag antenna with frequency.

## B. Cavity-backed elliptical spiral

One of the spiral antenna models we have recently investigated is a cavity-backed two-arm elliptical spiral antenna. We investigated the elliptical structure and observed whether the structure provides changes in beam-width as well as changes in the radiation pattern. Our results show that by using an elliptical spiral antenna, we were able to regulate the beam-width in two orthogonal planes, $\varphi=0^0$ and $\varphi=90^0$. A sample plot is shown below in Fig. 7.

### i. Gain and half-power beam-width

Table 3 shows the RHC gain, LHC gain, and half-power beam-width in two orthogonal planes for the 1.5:1 elliptical spiral.

### ii. Axial ratio

An elliptical structure allows for different beam-widths in 2 orthogonal planes. However, the axial ratio in lower frequencies of operation degrades significantly with increasing major to minor axis ratio. In the future, we hope to improve the axial ratio in the lower frequencies in our models. Figure 8 shows the boresight axial ratio for an elliptical spiral antenna.

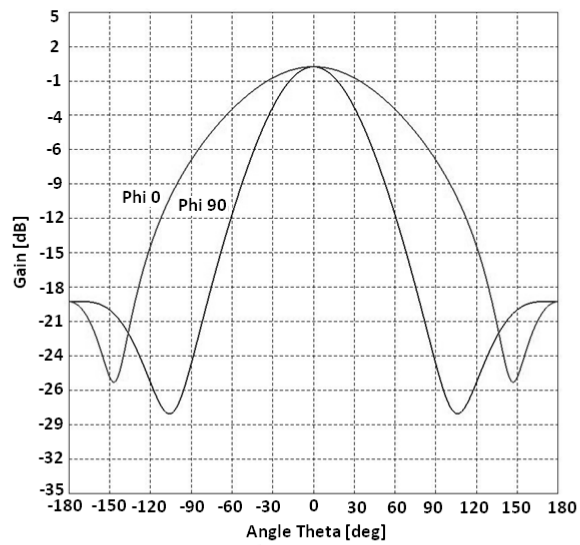



Fig. 7. Difference in half-power beam-widths in two principal planes of an elliptical spiral antenna at 2 GHz.

Table 3: Co-pol and cross-pol gain and 3dB beamwidth of optimized Archimedean elliptical spiral antenna

| AN 74 | Gain(dB) | | -3dB beam-width | |
|---|---|---|---|---|
| Freq (GHz) | LHC | RHC | Φ=0° plane | Φ=90° plane |
| 2 | -8.646 | 1.025 | 100 | 84 |
| 4 | -12.877 | 4.047 | 82 | 68 |
| 6 | -22.065 | 3.322 | 68 | 80 |
| 8 | -18.438 | 4.652 | 76 | 58 |
| 10 | -26.175 | 4.168 | 84 | 88 |
| 12 | -18.196 | 4.773 | 74 | 52 |
| 14 | -17.137 | 5.917 | 88 | 52 |
| 16 | -19.9 | 6.118 | 84 | 56 |
| 18 | -15.598 | 4.846 | 64 | 92 |

At the time of this work, the antennas are in the process of fabrication and we were not able to include measured results. However, we have addressed the general problem of the design and optimization of wideband lossy cavities from a microwave material characterization standpoint. Our procedure can be efficiently used for accurately designing and optimizing the dimensions of any broadband, cavity-backed Archimedean spiral antenna in general with precise frequency dependent electromagnetic properties of materials.

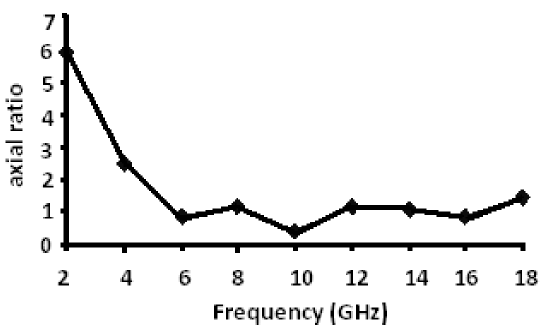



Fig. 8. Variation of axial ratio of the 1.5:1 elliptical antenna with frequency.

## VI. CONCLUSION

An effective design procedure for cavity-backed wideband antennas has been presented. We have approached the problem of determining the optimal dimensions of the lossy material inserted in the cavity by using microwave measurement techniques and subsequently applying the genetic algorithm optimization routine to arrive at a geometry that meets desired radiation specifications. Using frequency-dependent complex permittivity or permeability values allows us to accurately take advantage of the powerful computational tools that are commercially available to simulate radiation patterns that give closest approximation to actual measured patterns. This procedure can be extended to the design of any configuration of cavity-backed spiral antenna that uses multi-layered broadband dielectric or magnetic absorbing materials.

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