Design of Microstrip Hairpin Bandpass Filter for X-Band Radar Navigation

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Abstract— **Today radar has broad benefits in many areas, for example in telecommunications and military or civil applications for navigation. An important component that can improve the performance of a radar system is the filter. The function of the filter is to pass the desired frequencies and block the unwanted frequencies. This study discussed the design and realization of a bandpass filter using microstrip technology with a hairpin structure working at some parameters, namely frequencies, bandwidth, insertion loss, return loss and VSWR. The filter was realized using a Rogers 5880 substrate with a relative dielectric constant value of two point two and substrate thickness of 1.58 mm. A simulation was carried out using the CST Suite Studio software application. In realization result show that, the middle frequency value of the filter is equal to the specification and simulation, but there are differences result between the simulation and the realization, in insertion loss, return loss, bandwidth and voltage standing wave ratio (VSWR) values.**

***Key words* — bandpass; filter; hairpin; microstrip**

I. Introduction

The rapid development of telecommunication technology raises the demands from high-mobility society. The telecommunication equipment used, one of which is radar, should support all activities as well as possible.

Radar is a means of detecting the existence of an object by using electromagnetic waves. Generally, a radar operates by spreading limited electromagnetic forces inside an antenna dish. When the signal from an incoming object enters the antenna, it is captured and transmitted to the center of the radar system and then processed so that the object becomes visible on a monitor screen [1]. As a maritime country, Indonesia needs to develop radar to maintain security in its waters.

One of the most important components of the radar system is the filter. A radar filter is a circuit used to filter certain frequencies by passing the desired frequencies and dampening unwanted frequencies or those that are outside the working frequency of the filter. The types of filters used in telecommunication systems include the low pass filter (LPF), the high pass filter (HPF), the band pass filter (BPF), and the band stop filter (BSF). In well-used radar filter systems, a BPF type filter is used.

A BPF is a filter that passes the frequencies from the region between the first cut-off frequency and the second cut-off frequency and dampens the frequencies outside this range [2].

A microstrip is a transmission line consisting of a strip of conductors and a ground plane separated by a substrate with certain material characteristics [3]. One type of microstrip filter is a filter with a parallel coupled line configuration, but this filter has the disadvantage of having large physical dimensions. Another BPF is the analog type, which is quite expensive so its application in the manufacture of radar systems incurs a considerable cost.

To get the smaller filter size, the substrate must have higher relative permittivity value. The type of substrate also can increase the performance of the filter. The loss of the filter can be increased by choosing the right substrate. As an example, the Rodgers Duroid substrate has better loss performance than the common FR4 substrate [4].

In accordance with Regulation of the Minister of Communication and Information of the Republic of Indonesia Number 25, Year 2014 on Table of Allocation of Radio Frequency Spectrum of Indonesia, navigation radios operate within the frequency range of 9200-9800 MHz [5]. Based on this regulation, the frequency limits are entered as the X-band designation, which has a frequency range of 8-12 Ghz in accordance with IEEE (Institute of Electrical and Electronic Engineers) Standard 521-1984 [6].

In this research, a BPF was designed by using a microstrip and a hairpin filter substrate to be applied in a radar system that works in the frequency range of 9.25-9.35 GHz (X-band). Realization was done using PCB substrate Rogers 5880. The hairpin filter has a neatly arranged structure obtained by folding the parallel-coupled line resonator into a U-shape [2], which is commonly called a miniature hairpin resonator filter.

II. Theoretical Basis

A. Filter

A filter is a circuit designed to pass a certain frequency band while weakening all signals outside of this band. Another use of a filter is as a frequency selector circuit to enable passing a desired frequency and hold other

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frequencies. Filters can be grouped according to their frequency response, depending on the conditions and objectives of the filter system used, into LPF, HPF, BPF, and BSF [2]. LPF is filter that passes the frequencies below the cut-off frequency and dampens the frequencies above the cut-off frequency, HPF is a filter that only passes frequencies above the cut-off frequency and dampens frequencies that are below the cut-off frequency, BPF ihas two cut-off frequencie, and BSF is a band stop filter is the opposite of a BPF.

B. Microstrip Hairpin Filter

A microstrip filter is a transmission medium used in RF and microwave circuits. When the microstrip size is reduced so that its dimensions are smaller than the wavelength, the microstrip can be used as a lumped element.

One of the microstrip filter models is the hairpin filter. Hairpin filters fold half-wavelength microstrip lines into the "U" shape and then cascade them. The folded structure has the advantages of parallel-coupled filters and efectively reduce the size. Each half-wavelength microstrip line works as a resonator [7]. The hairpin method involves the development of a parallel-coupled line, where the λ / 4 coupled line channel is folded by L or ((λ / 4) -b), with b is the unpinned channel length.

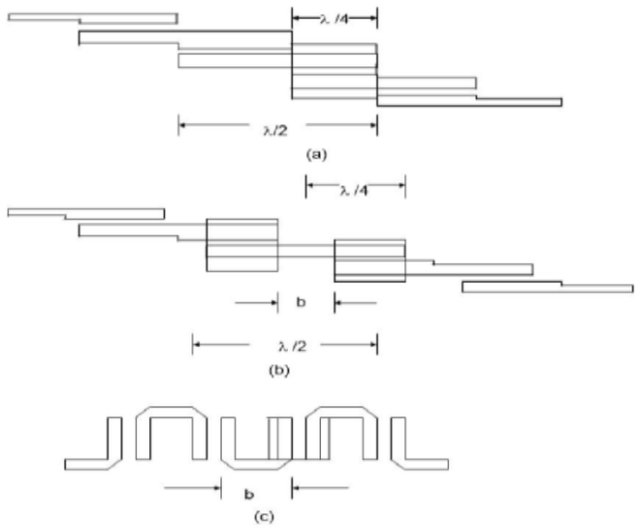

Fig. 1. Parallel-Coupled Line Transformation into Hairpin Filter [8]

C. Square Groove

The length and width of the square groove can be adjusted to increase the phase margin at both events and odds, thereby minimizing resonant frequency. The square groove is a Defected Ground Structure (DGS) technique that can produce smaller filter dimensions, eliminate harmonics and increase insertion loss and return loss [1,9].

D. Defected Ground Structure (DGS)

One of the electromagnetic bandgap (EBG) development techniques that has been studied is the defected ground structure (DGS). A DGS is a one-way EBG to suppress surface waves and is often used in microstrip antennas. The DGS structure is used on microstrip lines that reject certain frequencies. Various kinds of DGSs are shown in Fig. 2. [2].

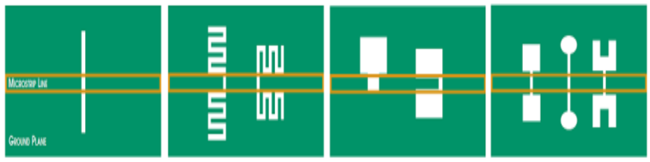

Fig. 2. Types of DGS

III. Research Methodology

The research for this final project used several methods. The main steps were: literature study, problem identification, needs analysis, design, simulation, realization, testing and analysis. The methodology of this research can be described using a flowchart or flow diagram as shown in *Fig. 3*.

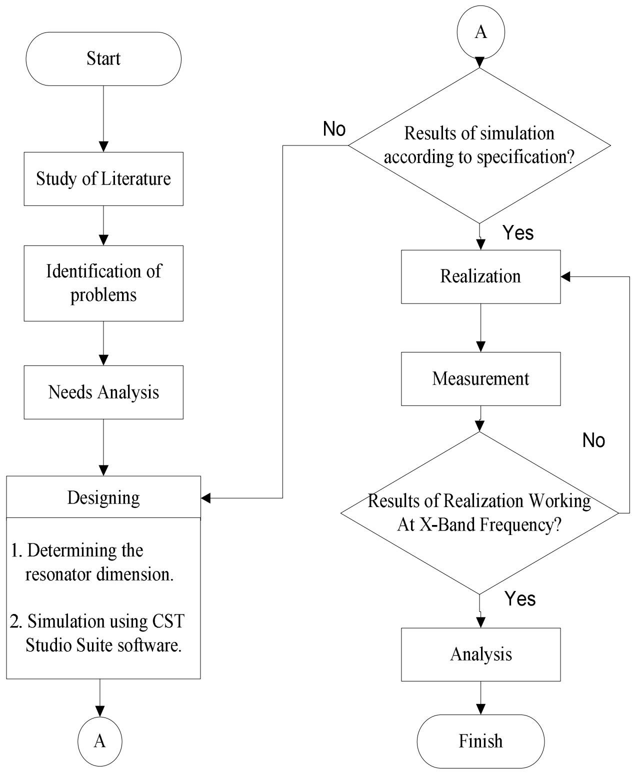

Fig. 3. Research Flowchart

IV. DESIGN, SIMULATION AND REALIZATION

In this final project, a BPF microstrip hairpin was designed that operates at a middle frequency of 9.3 Ghz. The designing was done in several stages. Each stage was executed thoroughly to minimize design errors and avoid decreased filter performance because of poor design.

A. Filter Design

The desired filter specifications are shown in Table I.

TABLE I. FILTER SPECIFICATIONS

BPF Parameter	Value
Start frequency (f1)	9.25 GHz
Stop frequency (f2)	9.35 GHz
Center frequency (fc)	9.3 GHz
Bandwidth	100 MHz
Filter Hairpin order	5 pole
Return loss	≤ -10 dB
Insertion loss	≥ -3 dB
VSWR	1-1.5
Matching impedance	50 ohm

The type of substrate used was Rogers 5880 with the specifications as listed in Table II:

TABLE II. SPECIFICATIONS OF SUBSTRATE USED [10]

Name of Specification	Specification
Substrate type	Rogers 5880
Relative dielectric constant (ε_r)	2.2
Substrate thickness (h)	1.58 mm

This filter can be applied in X-band radar system. Working at frequencies at 9.3 GHz. Used for navigation radar systems, aims to maintain the safety of Indonesian marine waters. And this research can add insight and knowledge about the implementation and realization of BPF microstrip.

B. Determination of Filter Dimensions

Determining the hairpin filter dimensions was done using Equations (1)-(16) [2,11].

1) Defining the filter order

The order of the filter can be determined from the damping characteristics curve based on the Chebyschev approach with 0.1 dB ripple, as follows:

$$\Delta = \frac{f_2 - f_1}{f_c} = \frac{9.25 \, x \, 10^9 - 9.35 \, x \, 10^9}{9.3 \, x \, 10^9} = 0.010752 \quad (1)$$

$$\frac{\omega}{\omega_c} = \frac{1}{\Delta}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) \quad (2)$$

$$\frac{\omega}{\omega_c} = \frac{1}{0.010752}\left(\frac{18.7\pi \, x \, 10^9}{18.5\pi \, x \, 10^9} - \frac{18.5\pi \, x \, 10^9}{18.7\pi \, x \, 10^9}\right) \quad (3)$$

$$\frac{\omega}{\omega_c} = 2.0001858$$

where ω is the stop frequency limit at 9.35 GHz, $\omega 0$ is the start frequency limit at 9.25 GHz, and fc is the center frequency T 9.3 GHz. From the filter damping curves for $\left|\frac{w}{w_c}\right| - 1 = 1.0001858$, with L_A = 60 dB and *ripple* 0.1, n ≥ 4 was obtained, so in the filter design n = 5 was used.

The values of the prototype element were as follows:

$g_0 = g_6 = 1$
$g_1 = g_5 = 1.1468$
$g_2 = g_4 = 1.3712$
$g_3 = 1.9750$

2) Determining the width of the resonator channel

The width of the resonator channel was determined with values $\varepsilon r = \mathbf{2.2}$, $h = 1.58 \, mm \, mm$ and $Zc = 50$ ohm and using the following formulas:

$$u = \frac{w}{h} = \frac{2}{\pi}\left\{(B-1) - \boldsymbol{ln}(2B-1) + \frac{\boldsymbol{\varepsilon r - 1}}{\boldsymbol{2\varepsilon r}}\left[\boldsymbol{ln}(B-1) + 0.39 - \frac{\boldsymbol{0.61}}{\varepsilon r}\right]\right\} \quad (4)$$

$$B = \frac{60\pi^2}{Zc\sqrt{\varepsilon r}}$$

$$= \frac{60.3.14^2}{Zc\sqrt{2.2}} = 7.9768$$

$$u = \frac{w}{h} = \frac{2}{\pi}\left\{(B-1) - ln(2B-1) + \frac{\varepsilon r - 1}{2\varepsilon r}\left[ln(B-1) + 0.39 - \frac{0.61}{\varepsilon r}\right]\right\}$$

$$= 3.077931769 > 2$$

Because $\frac{W}{h} > 2$, a thick substrate can be used: (h) = 1,58 mm. To determine the width of the resonator channel, the following equation was used:

$$W = u \, x \, h \quad (5)$$

$$= 4.86 \, mm$$

3) Determining the effective permitivity constants

For the dielectric constant (εeff) effective on the microstrip channel, the calculation was as follows:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10}{u}\right)^{-ab} \quad (6)$$

With $u = \frac{W}{h}$, and

$$\alpha = 1 + \frac{1}{49} ln\left[\frac{u^4 + \left(\frac{u}{52}\right)^2}{u^4 + 0.432}\right] + \frac{1}{18.7} ln\left[1 + \left(\frac{u}{18.1}\right)^3\right] \quad (7)$$

$$b = 0.564\left(\frac{\varepsilon_r - 0.9}{\varepsilon_r + 3}\right)^{0.053} \quad (8)$$

$\alpha = 1.000165122$ dan $b = 0.523517833$

So:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10}{u}\right)^{-ab}$$

$$= 1.901080934$$

4) Determining the length of the lambda microstrip

The calculation used for determining the length of the lambda microstrip was:

$$\lambda_{air} = \frac{c}{f_c} = \frac{3 \, x \, 10^8 \, m/s}{9.3 \, x \, 10^9 Hz} \quad (9)$$

$$= 0.032258064 \text{ mm}$$

$$\lambda_{microstrip} = \frac{\lambda udara}{\sqrt{\varepsilon_{eff}}} = 23.395805 \text{ mm} \quad (10)$$

5) Determining the sliding factor and length of the resonator arm

The value of the sliding factor, θ, cannot be determined exactly, so an assumed value was taken. θ was taken as 10^0

because this assumption is most widely used in hairpin filter design. The calculation was as follows:

$$b = \frac{\theta^0}{360^0}\ x\ \lambda_{mictostrip} \quad (11)$$

$$= 0.649883472\ mm$$

$$S_r = 2\ x\ b \quad (12)$$

$$= 1.299\ mm$$

The following equation determined the length of L:

$$L = \frac{\left(\frac{\pi}{180}\right)}{\sqrt{\varepsilon_{eff}.k_o}}\ x\ \theta^{\circ} \quad (13)$$

$$k_o = \frac{2.\pi.f}{c} = 194.68$$

So:

$$L = \frac{\left(\frac{\pi}{180}\right)}{\sqrt{\varepsilon_{eff}.k_o}}\ x\ \theta^{\circ} = 11.6\ mm$$

6) Determining the quality factor value

The value of the quality factor is calculated as follows:

$$Q = \frac{fc}{f1+f2} = \frac{9.3\ x\ 10^9}{9.35x10^9 - 9.25x10^9} = 93 \quad (14)$$

7) Determining the coupling coefficient

The coupling coefficient value is used to find the distance to resonator:

$$M_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \quad (15)$$

$$M_{1,2} = 0.068\ \text{mm}$$

$$M_{1,2} = M_{4,5} = 0.043\ \text{mm}$$

8) Determining the tap length

Tap length = 5 x h

= 7.9 mm

9) Determining the square groove

To get the value of the square groove the following equation is used:

$$W_r = \frac{1}{2}\ W \quad (16)$$

$$W_r = 2.43\ mm$$

Thus, the square groove value is 2.43mm x 2.43mm

C. Filter Simulation

A simulation of the filter was conducted using CST Suite Studio so that the output of the designed filter response could be seen.

The hairpin filter layout is shown in Fig. 4.

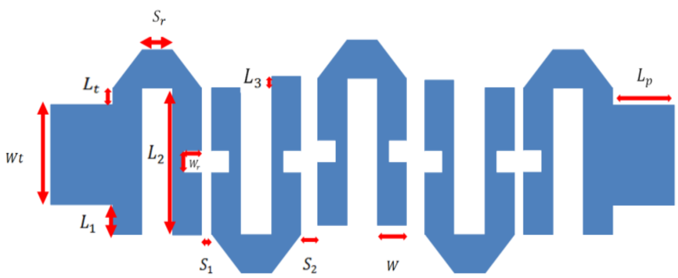

Fig. 4. Hairpin Filter Layout

The filter dimensions from the calculation results and the optimization results are shown in Table III.

TABLE III. FILTER DIMENSION

Filter Dimensions	Calculation Result (mm)	Optimization Result (mm)
Wt (mm)	4.86	4.75
W (mm)	4.86	1.7
L_t (mm)	0	0.2
L_1 (mm)	0.29	0
L_2 (mm)	5.15	4.43
L_3 (mm)	0	0.5
S_r (mm)	1.29	1.3
W_r (mm)	2.43	0.3
S_1 (mm)	0.068	0.2
S_2 (mm)	0.043	3
L_p (mm)	7.9	7

D. Result of Realization

At this stage the filter realization process was carried out using the Rogers 5880 substrate material. After the realization process, the next stage was the installation of connectors on both sides of the PCB. The connectors used in the filter realization were of the SMA type because their characteristics are suitable for small filter construction.

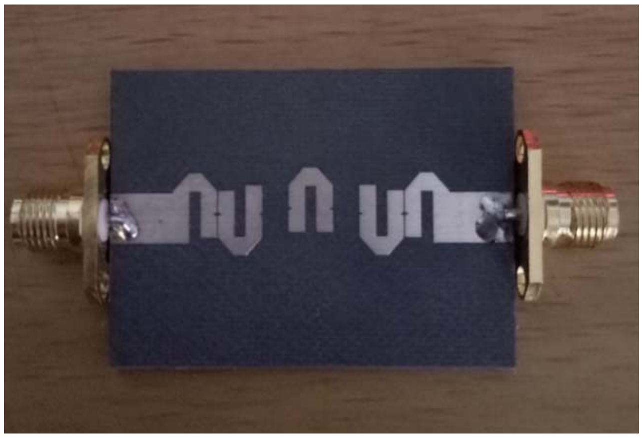

Fig. 5. Microstrip Hairpin Filter

E. Measurement and Analysis

Measurement of the realization result of the BPF hairpin was done by using an Advantest R3370 network analyzer with a working frequency vulnerability of 300 KHz-20 GHz. The realization was done to know if the filter's specifications were in accordance with the prior specifications, so its characteristics and performance could be known and analyzed. The parameters measured included insertion loss, return loss, bandwidth and voltage standing wave ratio (VSWR). A comparison of the simulation results and the realization results is shown in Fig. 6.

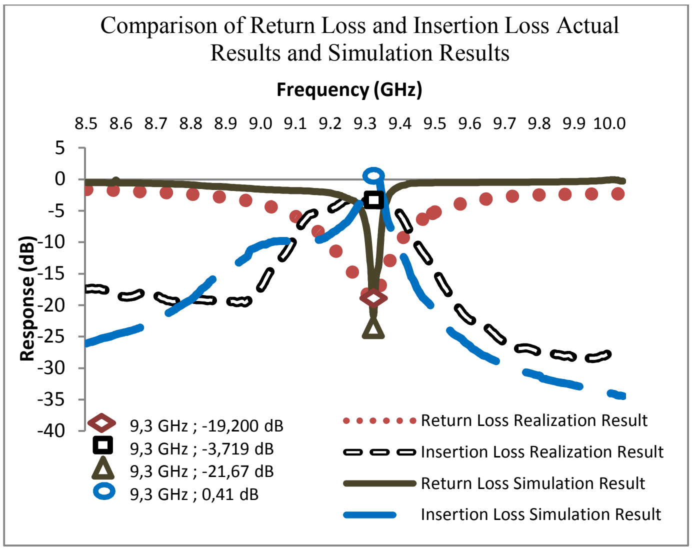

Fig. 6. Comparison of Return Loss and Insertion Loss Actual Results and Simulation Results

Table IV contains a comparison between the parameters of the specification, the realization results and the simulation results.

TABLE IV. COMPARISON OF SIMULATION RESULTS AND REALIZATION RESULTS OF HAIRPIN BPF

Parameter	Initial Specification	Simulation Result	Realization Result
Center Frequency (GHz)	9.3	9.3	9.3
Bandwidth (MHz)	(9.25 – 9.35 *GHz*) 100	(9.25 – 9.35 *GHz*) 100	(9.11 – 9.39 *GHz*) 280
Insertion Loss (dB)	≥ -3	0.41	-3.719
Return Loss (dB)	$\underline{\leq -10}$	-21.67	-19.200
VSWR	$1 - 1.5$	1.1	1.246

From the results in Table IV, the middle frequency of the simulation result and the realization result were both in accordance with the specification of 9.3 GHz. The bandwidth simulation results were in accordance with the specification of 100 MHz. However, the bandwidth in the realization result was different, i.e. it increased to 280 MHz. Even though the bandwidth in the realization result widened, this filter can still work at X-band frequencies, i.e. at the 8-12 GHz frequency band. The return loss value in the simulation result was -21.67 dB and the realization yield of -19.20 dB was in accordance with the specification, i.e. <-10 dB. The insertion loss value from the simulation result was very good, i.e. very close to 1 (0.41dB).

However, in the realization the value of insertion loss decreased to -3.719 dB. This value is not in accordance with the desired specification, i.e. ≥ -3 dB. The VSWR value of the simulation result was 1.1 and the realization result of 1.246 was still within the filter specification. Overall, it can be said that the results of the simulation and the realization were within the X-band frequency range.

F. Common Error Analysis

The differences between the simulation results and the realization results could have been caused by several factors. Factors affecting the realization result are:

- Improper filter printing.
- The type of substrate material used.
- The lead solder connection between the connectors and the microstrip causing losses.
- Temperature and air humidity.
- The realization was not done in ideal spatial conditions.

V. CONCLUSIONS AND SUGGESTIONS

A. Conclusions

The entire process, from the design and the realization of the hairpin BPF to the network analyzer measurement, can be summed up as follows:

1. In the simulation, the design results were in accordance with the specifications with optimization done 7 times. The middle frequency was at 9.3 GHz, the bandwidth was 100 MHz, the return loss was -21.67 dB, the insertion loss was 0.41 dB and the VSWR was 1.1. The design parameters were in accordance with the prior specifications.
2. The results of the measurement of the realized filter using a network analyzer revealed a middle frequency of 9.3 GHz while the bandwidth was 280 MHz, the return loss was -19,20 dB, the insertion loss was -3.719 dB and the VSWR was 1.246.
3. Analysis of the measurement results against the specification parameters was as follows:
   - The center frequency corresponded to the desired frequency of 9.3 GHz.
   - The return loss from the realization results at -19.20 dB was in accordance with the specification, i.e. ≤-10 dB. This result is good.
   - The insertion loss from the realization results was -3.719 dB. This value was lower than the specification of ≥- 3 dB so the insertion loss value was not in accordance with the specification.
   - The bandwidth from the realization results was larger than the specification and the simulation results, i.e. it was widened by 180 MHz, from 100 MHz to 280 MHz. Despite the widened bandwidth, the filter can still work in X-band radar, which operates at the 8-12 GHz frequency band.
   - The VSWR from the realization results was 1.246.

There were differences between the results of the simulation and the results of the realization. This is because in a simulation the conditions are ideal, while in realization many conditions can affect the results.

B. Suggestions

In the design development and realization of filters for navigation radar at X-band frequencies it is recommended to consider the suggestions below in order to obtain optimal results:

- In determining the parameter values for a filter that works at high frequencies, the calculation process must be done carefully. This will greatly affect the simulation and realization results because differences in the numbers behind the comma have a great influence.
- In the case of soldering the microstrip connector to the input or the output it is necessary to consider the neatness and thickness of the soldering because it can increase losses.
- At the time of printing the filter attention must be paid to the PCB board printer tool because its precision affects the filter results.
- Try installing a casing on the filter.
- It is worth trying to create filters for navigation radar applications working at X-band frequencies using other methods, such as fractal shapes.

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