Designing Microstrip Circuits with low-loss CuFlon Substrates

Microstrip is one of the most widely used transmission media at microwave frequencies. Because of its open-ended configuration, discrete and monolithic components are readily mounted on a microstrip substrate, for ease in production assembly, tuning and repair not possible with stripline. As will be seen, microstrip is well suited for use with Polyflon's CuFlon substrate, a pure PTFE material whose electrical and physical properties make it the ideal substrate for low-loss, high frequency circuits, especially above 5 GHz.

A basic microstrip circuit consists of a single microwave dielectric substrate, coated with a conductive metal transmission line of width w on one side and a metal ground plane on the other (Figure 1). Above the circuit there is nothing but air, so there is nothing above the circuit to apply pressure to the microwave laminate. To minimize pressure and make a good ground connection, the laminate is attached to a circuit enclosure or case by means of solder or conductive epoxy, rather than screws which can apply a great deal of localized pressure to the substrate.

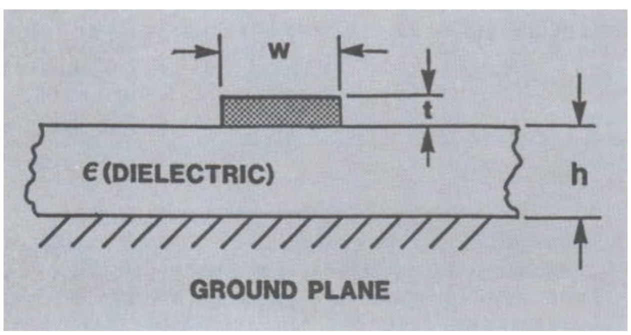

Figure 1. *MICROSTRIP*

Microstrip Evolution

Microstrip came into prominence in the mid-1960's with the growth of microwave integrated circuits (MICs). The transmission-line medium is particularly well suited to the integration of functions found in most MICs. Figure 2 illustrates the evolution of microstrip from the popular two-wire transmission line. Figure 2(a) shows how two wires with even spacing between them develop electric (E) and magnetic (H) fields. In Figure 2(b), the two wires have been compressed into flat conductors with essentially the same spacing between them. In Figure 2(c), a conducting plate called the ground plane has been placed at the plane of symmetry. In Figure 2(d), the final step in the evolutionary process places a thin slab of dielectric material, such as PTFE, between the two conductors (circuit and ground plane). Addition of the dielectric material creates an inhomogeneous transmission line, compared to the perfectly homogeneous two-wire transmission-line structure. The difference lies in the fact that in microstrip, the electric field extends into the dielectric material as well as the air around it.

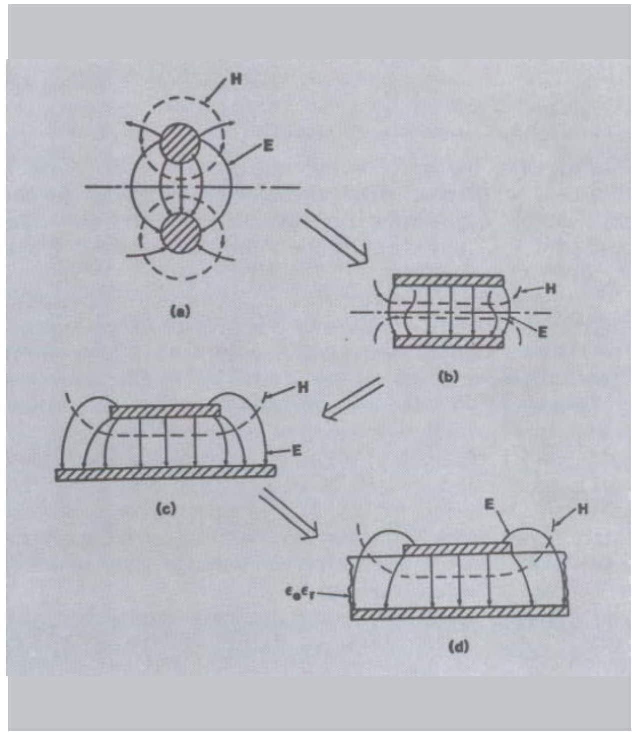

Figure 2: *Evolution of MICROSTRIP*

Basic Microstrip Principles

When designing microstrip circuits, two key parameters are characteristic impedance (Zo) and effective dielectric constant (εeff). The two parameters are directly related, since each different calculated impedance results in a different effective dielectric constant. This relationship is evident in equations (1) and (2):

For $W/h \leq 1$:

$$Z_o = (60/\sqrt{\varepsilon ff}) \ln (8h/W + 0.25W/h)$$

For $w/h \geq 1$:

$$Zo = (120\pi/\sqrt{\varepsilon ff})/(W/h + 1.393 + 0.667 \ln(W/h + 1.444))$$

where

εeff = the effective dielectric constant;
W = the width of the microstrip line; and
h = the thickness of the dielectric material.

Equations (1) and (2) were used to compute the results shown in the table below:

Table 1. Variations of εeff and Zo with W

Substrate Thickness (in.)	Width, W (in.)	Effective Dielectric Constant εeff	Characteristic impedance, Zo (ohms)
0.030	0.020	1.683	117.7
0.030	0.050	1.746	76.5
0.030	0.100	1.813	50.0

Notice that for each value of impedance, there is a different width and effective dielectric constant. As the microstrip line width is increased, the effective dielectric constant, εeff, increases and the characteristic impedance, Zo, decreases.

The term effective dielectric constant takes into account the inhomogeneous nature of microstrip. Since electric-field propagation in microstrip takes place in a microwave laminate as well as in the air above it, the dielectric properties of both media affect propagation. The microwave laminate has a relative dielectric constant (εr) which is determined by the characteristics of the substrate material. CuFlon, which is pure PTFE, has a relative dielectric constant of 2.1. PTFE substrates reinforced with glass have a higher relative dielectric constant, about 2.17. The relative dielectric constant of air, which is a lossless dielectric medium, is 1.

Since microstrip is an inhomogeneous transmission medium, the relative dielectric constant is actually of secondary importance when designing circuits. A more important parameter, the effective dielectric constant, accounts for the differences in electrical conditions above and below the microstrip circuit board.

The filling factor, q, is a quantity vital to the determination of the effective dielectric constant. The filling factor is the ratio of the microstrip dielectric area to the total area that would be used if the medium were an enclosed one like stripline. Figure 3 aids in determining the value of the filling factor for different cases. The vertical axis shows the shape ration, W/h, where W is the width of the microstrip conductor or line and h is the thickness of the substrate.

Figure 3 emphasizes the direct connection between the conductor width (and thus the characteristic impedance of a microstrip line) and the effective dielectric constant. By calculating a shape ratio, and moving across the graph until the filling factor curve is intersected, a designer can find a value for q. For example, a dielectric with a thickness of 0.030 in. and a line width of 0.075 in. yields a shape ratio of W/h = 0.075 in. /0.030 in. = 2.5. In Figure 3, a shape ratio of 2.5 translates into a filling factor of q = 0.7. This value of q can then be used then to find the effective dielectric constant for a line width of 0.075 in., using equation (3):

$$\varepsilon eff = 1 + q(\varepsilon r - 1)$$

where

εeff = the effective dielectric constant;
εr = the relative dielectric constant; and
q = the filling factor.

Equation (3) can be put to good use with CuFlon, assuming the filling factor, q, of 0.7 found in the example above. CuFlon, with a relative dielectric constant of 2.1, yields an effective dielectric constant of:

$$\varepsilon eff = 1 + 0.7\,(2.1 - 1) = 1 + 0.7\,(1.1) = 1.77.$$

This computed effective dielectric constant value of 1.77 for CuFlon matches closely with the value of 1.784 modeled with Compact Software for CuFlon that is 0.031 in. thick and has a 0.075 in. line width. This is well within the accuracy limits possible with Figure 3.

Tables 2-6 provide the effective dielectric constants for CuFlon with a relative dielectric constant of 2.1. CuFlon is shown in thicknesses of 0.005, 0.010. 0.020, 0.031, and 0.062 in. with a wide range of microstrip line widths. These data were generated with Compact Software, and are used in license agreement with Compact Software, Inc.

The example of equation (3) demonstrates the direct interaction between the characteristic impedance (Zo) of a microstrip line and the effective dielectric constant (εeff) of a microwave laminate. Both terms are necessary and vital for calculating circuit values in microstrip applications.

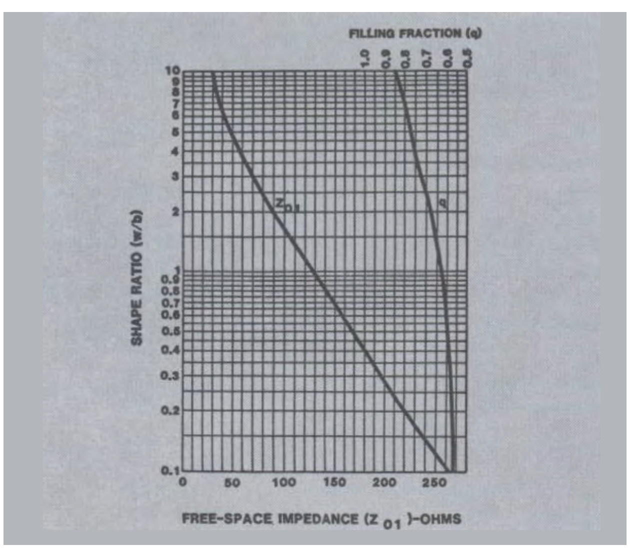

Figure 3: *MICROSTRIP Chart*

Microstrip Applications

Having now discussed the key parameters of microstrip, it's time to show how pure PTFE CuFlon material can be used in specific microstrip designs. Table 2-6 provide the means for determining, from particular impedance, the width of the associated microstrip line and its coinciding effective dielectric constant. Given those values, it will then be possible to create a circuit.

Example 1

Microwave power dividers serve to split an input signal into two or more output signals of equal amplitude. A typical two-way microstrip power divider for use at 20 GHz can be readily built from 0.031-inch-thick CuFlon material. But first, the dimensions of the divider must be determined.

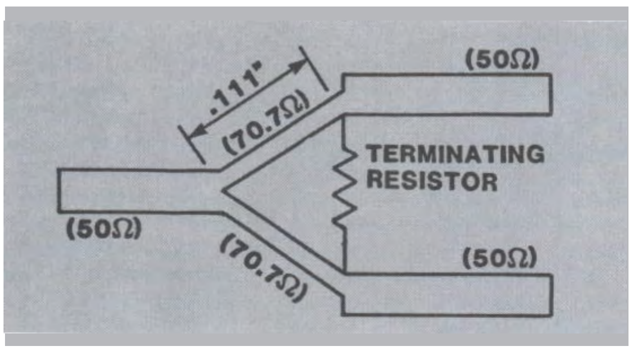

Figure 4: *Power Divider Example*

A Wilkinson-type power divider (Figure 4) is the simplest design possible. The input and output lines are 50 ohms, while the transition lines, between the input and output, have an impedance of 70.7 ohms.

Table 5 provides the following values of impedance, line width, and effective dielectric constant for a 20 GHz, two-way Wilkinson power divider:

Characteristic Impedance, Zo (Ohms)	Line width, W (in.)	Effective dielectric constant
50.0	0.100	1.813
70.7	0.055	1.755

The (λ) wavelength of the 70.7-ohm line at 20 GHz can be calculated by using a simple formula:

$\lambda = c/F \sqrt{\varepsilon eff}$

where

c = the speed of light (3 x 1010 cm/sec) and

F = frequency (in Hz).

To find the quarter wavelength (λ/4) of this power divider for the effective dielectric constant of 0.031-inch-thick CuFlon, the calculation is performed with equation (4):

$\lambda/4=c/(F\sqrt{\varepsilon eff}\ \times 4)$

Substitution of the known values of c, F, and εeff at 70.7 ohms into equation (4) yields:

$\lambda/4=(3 \times 1010 \text{ cm/sec})/(2 \times 1010 \sqrt{1.75} \times 4)$

Performing a similar calculation for the 50-ohm lines, equation (4) provides a value of 0.100 in. Using these two line lengths, the power divider of Figure 4 was constructed on 0.031-inch-thick CuFlon. To achieve similar low loss and isotropic performance with a substrate other that CuFlon, a hard, ceramic alumina substrate must be used. As a comparison, a 0.025-inch-thick alumina substrate with an effective dielectric constant of 6.43 was chosen to fabricate a 20-GHz, two-way Wilkinson power divider. Equation (4) shows the width dimensions for the 50-ohm line to be 0.012 in. and the 70.7-ohm line to be a 0.009 in. The quarter wavelength is 0.058 in.

A 20 GHz power divider built on alumina would be extremely small, making it virtually impossible to accurately place and attach the required terminating resistor to the circuit. With CuFlon, however, the 20 GHz, two-way power divider can be manufactured simply and repeatably. The power divider also would have the advantage of a low-loss, isotropic material in its construction.

Example 2

Directional couplers are often used in microwave systems to sample RF energy. A coupler consists of narrowly spaced microstrip lines, forming both coupled and through signal paths. Some simple design steps must be taken to build a microstrip coupler.

First, the dimensions of the coupler must be determined. For operation at 16 GHz, a spacing of 0.005 in. is required between the lines, and the impedance at the coupling area must be 103 ohms. Table 4 indicates that 103 ohms is equivalent to a 0.018 in. line width, having an effective dielectric constant of 1.69.

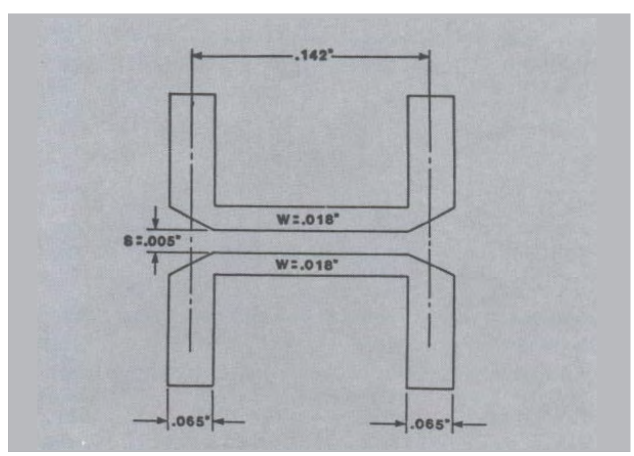

Figure 5: *Directional Coupler Example*

The next step is to calculate the quarter wavelength for the coupled section. This is done with equation (5):

$$\lambda/4 = c/(F\ (2.54)\ \sqrt{\varepsilon eff}\ \ x\ 4)$$

$$= (3\ x\ 1010\ cm)/(1.6\ x\ 1010\ (2.54)\ \sqrt{1.69}\ x\ 4)$$

$$= 0.142\ in.$$

Applying the information derived from these calculations to the design of the coupler, the 10 dB coupler shown in Figure 5 was built. To achieve similar coupling performance with a 0.025 –inch-thick alumina substrate with eff = 6.43, the following parameters would apply:

50-ohm line = 0.012 in. wide;

103-ohm line = 0.0015 in. wide;

quarter wavelength = 0.073 in. long.

Given these dimensions, it is obvious that alumina is not practical for fabricating a 10 dB coupler at 16 GHz. The quarter-wavelength lines yield input and output lines that are too close together to reproduce in a production environment. Also, the coupling section would be too narrow to be repeatably duplicated. Fortunately, CuFlon does not exhibit these drawbacks. It yields a 16 GHz coupler of a reasonable size and, because of its low dielectric constant and isotropic nature, provides excellent performance.

General Applications

From the examples presented above, it is apparent that CuFlon and microstrip work well together in high-frequency applications. Pure PTFE CuFlon provides a low dielectric constant that is ideal for microstrip circuits operating at frequencies of 5 GHz to millimeter waves.

Two primary parameters of CuFlon support its use at high microwave frequencies: isotropy and dissipation factor. For CuFlon, these parameters translate into very low-loss performance at much higher frequencies than possible with composite PTFE/glass substrates.

Isotropy indicates the consistency of a material. In microwave substrates, glass or fiberglass are often added to improve dimensional stability, at the cost of isotropy. The dielectric constants of these composite materials are different in the X-Y direction than in the Z direction. The different is gauged in terms of negative isotropy or anisotropy. The anisotropy of PTFE/glass substrates is always greater than 1, usually 1.02 to 1.20, since these substrates are not completely homogeneous. CuFlon is pure PTFE material without need of reinforcing agents and has an ideal anisotropy value of 1.0. The dielectric constant of CuFlon is precisely the same in the X, Y, and Z directions for the most uniform possible RF performance.

Dissipation factor is a measure of the conducting characteristics of a microwave material. For a typical PTFE/glass laminate, the dissipation factor is on the order of 0.009 at a dielectric constant of 2.17;0.0012 for a dielectric constant of 2.33; 0.0018 for a dielectric constant of 2.50; and 0.002 for a dielectric constant of 10.2 CuFlon exhibits a dissipation factor of no greater than 0.00045 at 1 GHz, decreasing to below 0.00025 at frequencies past 20 GHz. Comparison of these numbers shows how CuFlon can be an excellent choice for higher microwave frequency operation, where unwanted signal losses can mean the difference between success and failure.

The overall characteristics of CuFlon make it the ideal microstrip substrate material at microwave to millimeter-wave frequencies. By using CuFlon in a microstrip medium, its characteristics can be used to their utmost advantage.

Table 2: h = .005”

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W Mils	Zo ohms	V E+08 M/SEC	εeff
5.000	97.462	2.293	1.709
10.000	67.668	2.256	1.766
15.000	52.502	2.231	1.806
20.000	43.099	2.212	1.836
25.000	36.643	2.198	1.860
30.000	31.916	2.187	1.879
35.000	28.296	2.178	1.895
40.000	25.429	2.170	1.909
45.000	23.101	2.163	1.921
50.000	21.170	2.158	1.931
55.000	19.541	2.153	1.940
60.000	18.149	2.148	1.947
65.000	16.945	2.144	1.954
70.000	15.892	2.141	1.961
75.000	14.965	2.138	1.967
80.000	14.140	2.135	1.972
85.000	13.403	2.132	1.977
90.000	12.739	2.130	1.981
95.000	12.139	2.128	1.985
100.000	11.593	2.126	1.989
105.000	11.094	2.124	1.992
110.000	10.637	2.122	1.996
115.000	10.217	2.121	1.999
120.000	9.828	2.119	2.002
125.000	9.468	2.118	2.004
130.000	9.134	2.116	2.007
135.000	8.823	2.115	2.009

140.000	8.532	2.114	2.012
145.000	8.260	2.113	2.014
150.000	8.005	2.112	2.016
155.000	7.765	2.111	2.018
160.000	7.540	2.110	2.019
165.000	7.327	2.109	2.021
170.000	7.125	2.108	2.023
175.000	6.935	2.107	2.025
180.000	6.755	2.106	2.026
185.000	6.583	2.105	2.027
190.000	6.420	2.105	2.029
195.000	6.266	2.104	2.030
200.000	6.118	2.103	2.032
205.000	5.977	2.103	2.033
210.000	5.843	2.102	2.034
215.000	5.714	2.101	2.035
220.000	5.592	2.101	2.036
225.000	5.474	2.100	2.037
230.000	5.361	2.100	2.039
235.000	5.251	2.099	2.041
240.000	5.148	2.098	2.041
245.000	5.052	2.100	2.038
250.000	4.959	2.101	2.036
255.000	4.862	2.099	2.041
260.000	4.748	2.087	2.064
265.000	4.662	2.086	2.065
270.000	4.606	2.098	2.042
275.000	4.544	2.106	2.027
280.000	4.466	2.105	2.028
285.000	4.361	2.091	2.056
290.000	4.213	2.053	2.132
295.000	4.144	2.053	2.135
300.000	4.124	2.075	2.087

Table 3: h = .010”

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W MILS	Zo ohms	V E+08 M/SEC	εeff
5.000	129.753	2.319	1.671
10.000	97.462	2.293	1.709
15.000	79.562	2.273	1.740
20.000	67.668	2.256	1.766
25.000	59.063	2.242	1.787
30.000	52.502	2.231	1.806
35.000	47.315	2.221	1.822
40.000	43.099	2.212	1.836
45.000	39.599	2.205	1.849
50.000	36.643	2.198	1.860
55.000	34.111	2.192	1.870
60.000	31.916	2.187	1.879
65.000	29.994	2.182	1.888
70.000	28.296	2.178	1.895
75.000	26.784	2.174	1.902
80.000	25.429	2.170	1.909
85.000	24.208	2.166	1.915
90.000	23.101	2.163	1.921
95.000	22.092	2.160	1.926
100.000	21.170	2.158	1.931
105.000	20.322	2.155	1.935
110.000	19.541	2.153	1.940
115.000	18.819	2.150	1.944
120.000	18.149	2.148	1.947
125.000	17.526	2.146	1.951
130.000	16.945	2.144	1.954
135.000	16.402	2.143	1.958
140.000	15.892	2.141	1.961
145.000	15.414	2.139	1.964
150.000	14.965	2.138	1.967
155.000	14.541	2.136	1.969
160.000	14.140	2.135	1.972
165.000	13.761	2.134	1.974
170.000	13.403	2.132	1.977
175.000	13.062	2.131	1.979
180.000	12.739	2.130	1.981
185.000	12.432	2.129	1.983
190.000	12.139	2.128	1.985
195.000	11.859	2.127	1.987
200.000	11.593	2.126	1.989
205.000	11.338	2.125	1.991
210.000	11.094	2.124	1.992
215.000	10.861	2.123	1.994
220.000	10.637	2.122	1.996
225.000	10.423	2.121	1.997
230.000	10.217	2.121	1.999

235.000	10.019	2.120	2.000
240.000	9.828	2.119	2.002
245.000	9.645	2.118	2.003
250.000	9.468	2.118	2.004
255.000	9.298	2.117	2.006
260.000	9.134	2.116	2.007
265.000	8.976	2.116	2.008
270.000	8.823	2.115	2.009
275.000	8.675	2.114	2.010
280.000	8.532	2.114	2.012
285.000	8.394	2.113	2.013
290.000	8.260	2.113	2.014
295.000	8.131	2.112	2.015
300.000	8.005	2.112	2.016

Table 4: h= .020”
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W MILS	Zo ohms	V E+08 M/SEC	εeff
5.000	162.856	2.336	1.647
10.000	129.753	2.319	1.671
15.000	110.690	2.305	1.692
20.000	97.462	2.293	1.709
25.000	87.475	2.282	1.725
30.000	79.562	2.273	1.740
35.000	73.087	2.264	1.753
40.000	67.668	2.256	1.766
45.000	63.051	2.249	1.777
50.000	59.063	2.242	1.787
55.000	55.578	2.236	1.797
60.000	52.502	2.231	1.806
65.000	49.766	2.226	1.814
70.000	47.315	2.221	1.822
75.000	45.104	2.216	1.829
80.000	43.099	2.212	1.836
85.000	41.272	2.208	1.843
90.000	39.599	2.205	1.849
95.000	38.062	2.201	1.855
100.000	36.643	2.198	1.860
105.000	35.330	2.195	1.865
110.000	34.111	2.192	1.870
115.000	32.976	2.189	1.875
120.000	31.916	2.187	1.879
125.000	30.925	2.184	1.884
130.000	29.994	2.182	1.888
135.000	29.120	2.180	1.892
140.000	28.296	2.178	1.895
145.000	27.519	2.175	1.899
150.000	26.784	2.174	1.902
155.000	26.089	2.172	1.906
160.000	25.429	2.170	1.909
165.000	24.803	2.168	1.912
170.000	24.208	2.166	1.915
175.000	23.641	2.165	1.918
180.000	23.101	2.163	1.921
185.000	22.585	2.162	1.923
190.000	22.092	2.160	1.926
195.000	21.621	2.159	1.928
200.000	21.170	2.158	1.931
205.000	20.737	2.156	1.933
210.000	20.322	2.155	1.935
215.000	19.924	2.154	1.937
220.000	19.541	2.153	1.940
225.000	19.173	2.151	1.942
230.000	18.819	2.150	1.944
235.000	18.478	2.149	1.946
240.000	18.149	2.148	1.947
245.000	17.832	2.147	1.949
250.000	17.526	2.146	1.951
255.000	17.231	2.145	1.953
260.000	16.945	2.144	1.954
265.000	16.669	2.144	1.956
270.000	16.402	2.143	1.958
275.000	16.143	2.142	1.959
280.000	15.892	2.141	1.961
285.000	15.650	2.140	1.962
290.000	15.414	2.139	1.964
295.000	15.186	2.139	1.965
300.000	14.965	2.138	1.967

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