Semester S1

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Foundations of electromagnetic wave propagation

Practical Work PW6

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Directional couplers in rectangular waveguide technology

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1. INTRODUCTION

The main objective of this practical work is the application of directional couplers and rectangular waveguides theory for the realization of a directional coupler with actual industry performances. This study will start discussing theoretical concepts of directional couplers, followed by the design and simulation steps with finite elements full-wave simulator (HFSS) to calculate the electromagnetic (EM) fields behavior and S parameters of the structure. In the end, an optimization step will be required to achieve the final specifications.

2. STUDY OF THE DIRECTIVE COUPLER

The directive coupler is compound by a main rectangular waveguide and rectangular waveguides (second lines) transversal to the main line. The 4-ports proposed device is shown in figure 1. As can be seen, ports 1 and 2 are placed in the main line exciting the rectangular waveguide fundamental mode TE_{10} while ports 3 and 4 excite the TEM mode in the coaxial waveguides. Couplings between main and second lines are performed through S42 and S31 coupling values.

To begin with the design, simulations of secondary lines are proposed as start point (figure 2). One of the sides of the line is terminated with a coaxial-to-waveguide transition, while on the other, a conical absorbent material is attached to a metal wall. The function of the absorbent material is to resemble as a matching load to the waveguide by absorbing the incident energy.

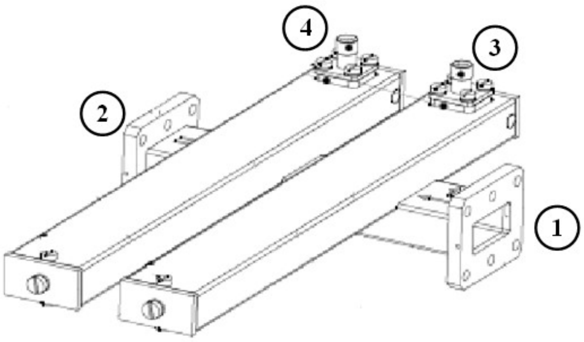


***Figure 1:** directional coupler (www.inoveos.com)*

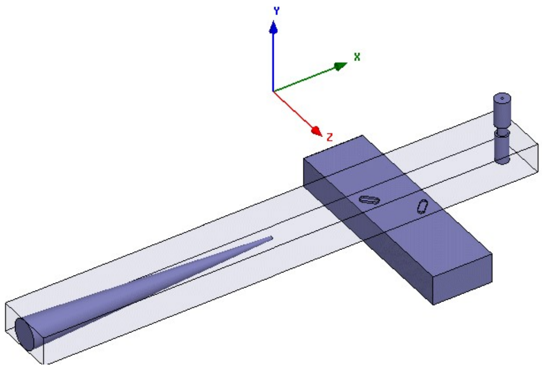


Figure 2: main and second lines in HFSS

2.1. Theoretical concepts

A directional coupler is an octopole joining together two guides (or transmission lines) in such a way that the guides of the same pair (1) and (2) or (3) and (4) are decoupled.

According to the diagram of generic directive couplers in figure 3, the port (1) is coupled to the ports (3) and (4) and decoupled from the port (2).

On the other hand, the port (3) is coupled to the ports (1) and (2) and decoupled from the port (4).

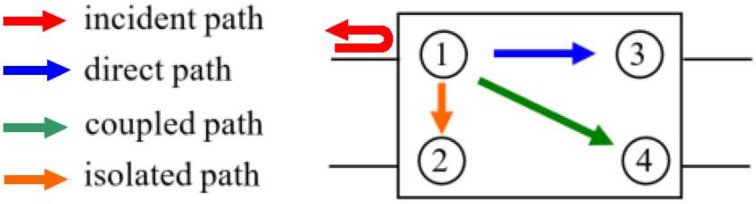


***Figure 3:** directional coupler generic diagram.*

From figure 3 it is also possible to define the following relative magnitudes associated to couplers:

- Coupling (dB) = $20.\,log\;|S_{41}|$
- Matching (dB) = $20.\,log\;|Sii|$
- Insertion Losses (dB) = $20.\,log|S_{31}|$
- Isolation (dB) = $20.\,log|S_{21}|$
- Directivity (dB) = $Coupling\;(dB) - Isolation(dB)$
- Relative Bandwidth (Hz) = $\frac{f2-f1}{fo}$

Furthermore, couplings can be classified in two different types: backward-wave and forward-wave (figure 4).

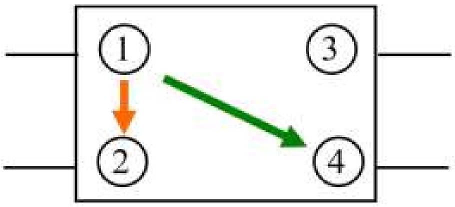


***Figure 4:** backward-wave (orange) and forward-wave (green) paths.*

Generic octopoles behavior can be expressed with S parameters matrix as shown in equation 1.

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \qquad (1)$$

By definition, couplers are reciprocal when Sij=Sji (with i different from j) and adapted if Sii = 0. Thus, in the case of perfect couplers:

- all the ports are matched ($S_{11} = S_{22} = S_{33} = S_{44} = 0$).

- the ports (1) and (2) (and respectively (3) and (4)) are isolated ($S_{21} = S_{12} = S_{43} = S_{34} = 0$).

- the module of the transmission coefficient in waveguides is close to one and therefore $s31 = s13 = s42 = s24 = \varepsilon . e^{J\theta}$, with ε the directivity and θ the phase coefficient.

- the transmission between waveguides in diagonal is $S_{41} = S_{14} = S_{32} = S_{23} = \kappa . e^{J\xi}$, with κ the coupling and ξ the phase coefficient.

$$[S] = \begin{bmatrix} 0 & 0 & \varepsilon . e^{J\theta} & \kappa . e^{J\xi} \\ 0 & 0 & \kappa . e^{J\xi} & \varepsilon . e^{J\theta} \\ \varepsilon . e^{J\theta} & \kappa . e^{J\xi} & 0 & 0 \\ \kappa . e^{J\xi} & \varepsilon . e^{J\theta} & 0 & 0 \end{bmatrix} \quad (2)$$

For reciprocal multipoles (isotropic properties) and without losses $[S]^T.[S]^*=[I]$. Therefore, if this expression is applied in equation 2, it can be demonstrated that the output EM waves on ports 3 and 4 are in quadrature (equation 3).

$$\begin{cases} \varepsilon . e^{J\theta}\left[\varepsilon . e^{J\theta}\right]^* + \kappa . e^{J\xi}\left[\kappa . e^{J\xi}\right]^* = 1 \\ \varepsilon . e^{J\theta}\left[\kappa . e^{J\xi}\right]^* + \kappa . e^{J\xi}\left[\varepsilon . e^{J\theta}\right]^* = 0 \end{cases} \Rightarrow \begin{cases} \varepsilon^2 + \kappa^2 = 1 \\ cos\ (\theta - \xi) = 0 \end{cases} \Rightarrow \begin{cases} \varepsilon^2 + \kappa^2 = 1 \\ \xi = \theta \pm \dfrac{\pi}{2} \end{cases} \quad (3)$$

3. SPECIFICATIONS AND MATERIALS

The required specifications for the design are the following:

- Bandwidth = 8.2 – 12.4 GHz (X Band)
- Central frequency = 10 GHz
- Coupling = 20 dB ± 1.5 dB
- Directivity > 18 dB
- Insertion losses < -1 dB
- $VSWR_{max}$ = 1.15 dB (rectangular waveguide)
- $VSWR_{max}$ = 1.2 dB (coaxial line)

The materials to be used on the waveguides and terminations of this practical work are:

- Absorbant: Alkard SF75 (see Dedienne Multiplasturgy documentation in Appendix I).
- Coaxial waveguide: SMA connector (see Amphenol Connex documentation in Appendix II).
- Rectangular waveguide: WR90 Aluminum (see Appendix III).

Further information can be found in Appendix.

4. CONDUCT STUDIES

The analysis will be performed in the X band (8.2-12.4 GHz). It is encouraged to optimize the matching, couplings and insertion losses of the final design. In order simplify the study it will be divided in several tasks: rectangular waveguide matched load analysis, coaxial-to-rectangular waveguide coupling analysis, coupling of two cross rectangular waveguides and optimization and global diagnosis of the structure.

4.1. Rectangular waveguide matched load analysis

This analysis consists on the optimization of the conical load dimensions (height and base diameter). To match the termination with the waveguide in the fundamental mode TE10 and avoid reflections, the final matching magnitude within the frequency band must be less than -25 dB.

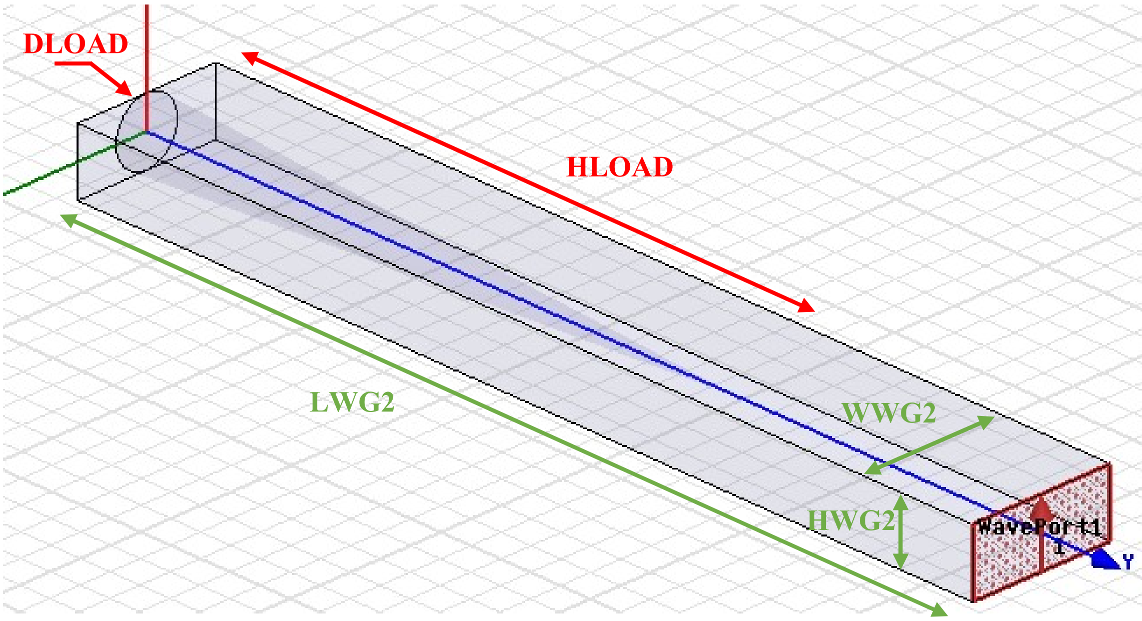


Figure 5: rectangular waveguide with matched load termination.

Some considerations

For the whole design consider air filled waveguides with perfect conductor (no metallic losses on the metal walls) and the load made in ALKARD SF. Remember that the electric and magnetic loss tangent represent the electromagnetic losses on the media and that for dielectric materials it can be expressed as in equations 4 and 5 :

$$tan\ \delta = \frac{\varepsilon_r''}{\varepsilon_r'} \quad (4)$$

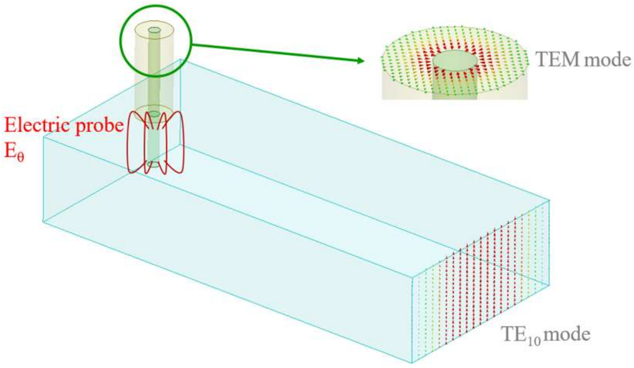
$$tan\ \delta = \frac{\mu_r''}{\mu_r'} \quad (5)$$

Suggested variable names

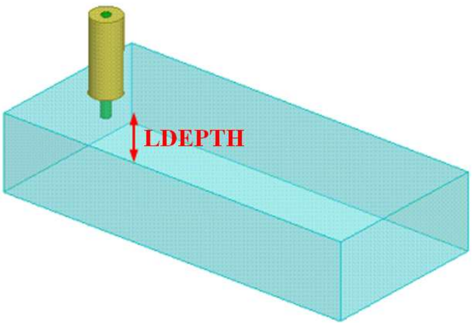
- ***LWG2: secondary waveguide length***
- ***HWG2: secondary waveguide height***
- ***WWG2: secondary waveguide width***
- ***DLOAD: load diameter***
- ***HLOAD: load heigth***

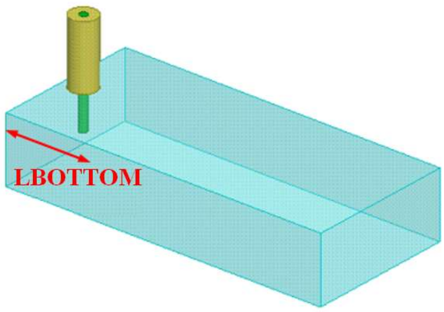
4.2. Coaxial to rectangular guide coupling analysis

In this step, good matching and insertion loss greater than $-1\ dB$ should be obtained by optimizing the coaxial to rectangular transition. Coaxial connector position, central conductor depth and length of the rectangular waveguide are some of the suggested parameters to improve the coupling. The central conductor of the coaxial connector is made in copper (ρ=58 S/um) while the dielectric surrounding it is made in Teflon, whose permittivity and dielectric loss tangent values can be considered as εr=2.1 and $tan\ \delta$=1.10^{-4} respectively (Appendix II).



(a)





(b) (c)

Figure 6: *coaxial-to-waveguide transition: (a) transmission modes and dimensions variations for optimization (b) and (c).*

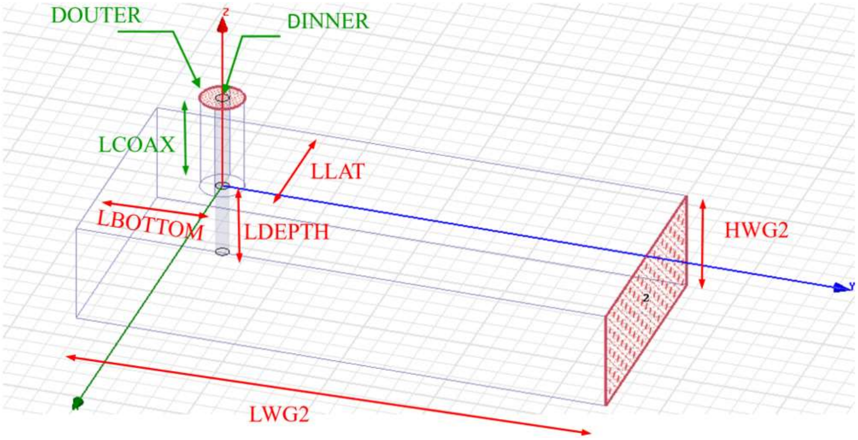


Figure 7: coaxial-to-waveguide transition variables.

Suggested variable names

- ***LWG2: secondary waveguide length***
- ***HWG2: secondary waveguide height***
- ***WWG2: secondary waveguide width***
- ***LCOAX : coaxial connector length***
- ***DOUTER: coaxial connector outer diameter***
- ***DINNER: coaxial connector inner diameter***
- ***LDEPTH: coaxial connector depth***
- ***LBOTTOM: coaxial connector Y position***
- ***LLAT: coaxial connector X position***

4.3. Coupling of two cross rectangular waveguides

As shown in figure 8, transversal guides are coupled to the main line by mean of two orthogonal (90°) slots separated a quarter-wavelength between each other ($d_1 = d_2 = \lambda_g/4$ at the central frequency). To obtain the desired specifications of the final device, slot dimensions (Sx and Sy) optimization procedure must be performed. To optimize the response, Sx, Sy, d1, d2 and t are some of the recommended parameters to be explored.

Due to technical limitations of the manufacturing process, slot rounded corners (r = 1.7 mm) and waveguide wall thickness (t = 1.5 mm) should be taken into account during this design step (figure 9). Nevertheless, it is possible to reduce the slots thickness and increase the coupling by machining the surface of one of the waveguide faces.

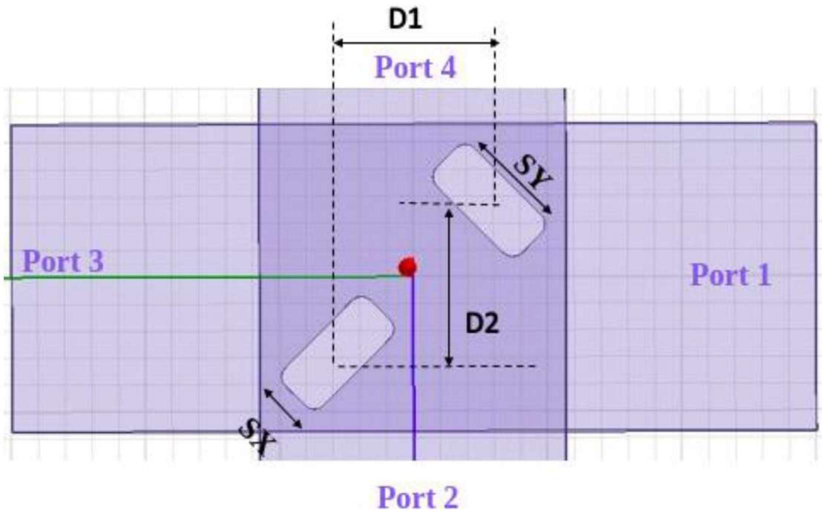
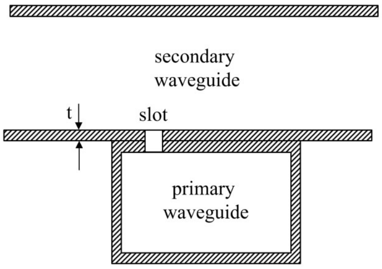
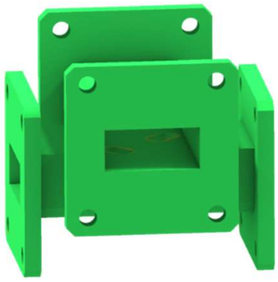


Figure 8: main to second line coupling analysis.



(a)



(b)

Figure 9: the two stacked guides (a) and the DA0 coupler with standard flanges (b).

Suggested variable names

- ***LWG1: main waveguide length***
- ***HWG1: main waveguide height***
- ***WWG1: main waveguide width***
- ***LWG2: secondary waveguide length***
- ***HWG2: secondary waveguide height***
- ***WWG2: secondary waveguide width***
- ***SX: slot width***
- ***SY: slot length***
- ***D1: horizontal distance between slot and waveguides intersection centres***
- ***D2: vertical distance between slot and waveguides intersection centres***
- ***T: slot thickness***

4.4. Global diagnosis of the structure and optimization

The final 2-ports directional coupler should resemble as the one depicted in figure 10. Simulations of the design should be performed in order to verify if the response is in good agreement with the desired specifications or if a final optimization step should be applied.

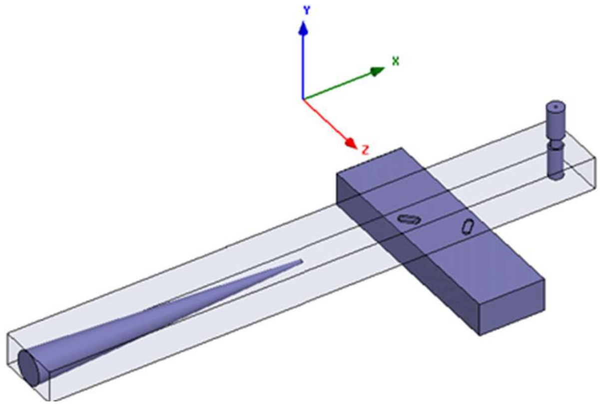
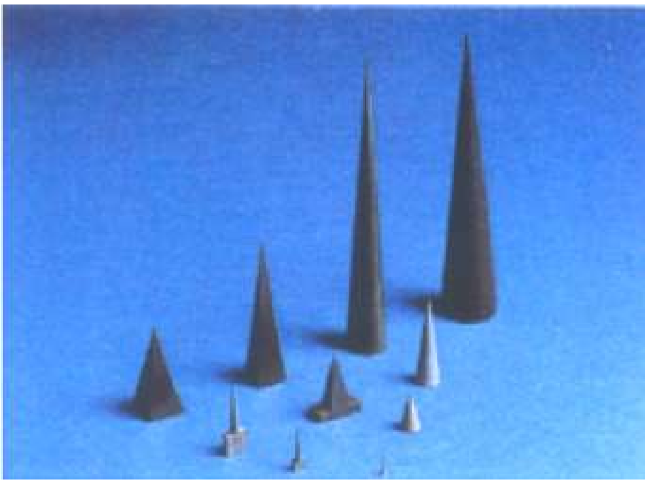


Figure 10: *final 2-ports directional coupler.*

APPENDIX I



Conical loads

ALKARD 75 loads are manufactured with the greatest care. They present along the band of every type of guide shown below a SWR =1,01. A threaded hole is drilled on the back to facilitate the mounting. These absorbent cones are matched to be used as reference for calibration or for directional coupler loads. For different sizes or shapes, don't hesitate in consulting us.

SWR measurements can be done on demand in the test bench provided by the client within the limits of our equipment.

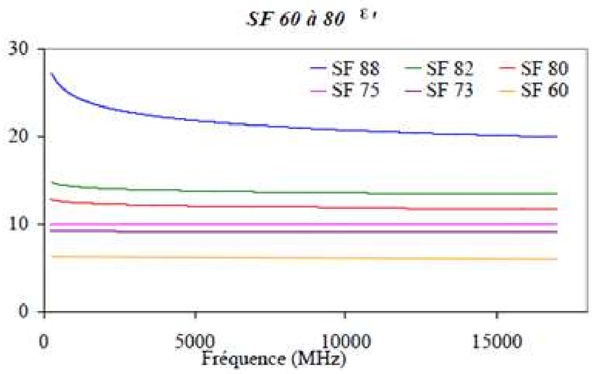
Reference	Guide type WR	Frequency band /GHZ	Total length /mm	Tapping and depth /mm	Power /W
284 C 75	284	2.6 - 3.95	280	8/ 30	10
229 C 75	229	3.3 - 4.9	240	8/ 30	8
187 C 75	187	3.95 - 5.85	220	6/ 25	5
159 C 75	159	4.9 - 7.05	190	6/ 25	4
137 C 75	137	5.85 - 8.20	180	4/ 20	4
112 C 75	112	7.05 - 10	130	4/ 20	3
90 C 75	90	8.2 - 12.4	100	3/ 10	2
75 C 75	75	10.0 - 15	80	3/ 10	1
62 C 75	62	12.4 - 18	76	3/ 10	1
42 C 75	42	18 - 26.5	60	2/ 5	0.5
28 C 75	28	26.5 - 40	41	2/ 5	0.5
22 C 75	22	33 - 50	30	1/ 5	0.25
15 C 75	15	50 - 75	20	0.8/ 5	0.1
12 C 75	12	60 - 90	20	0.8/ 5	0.1

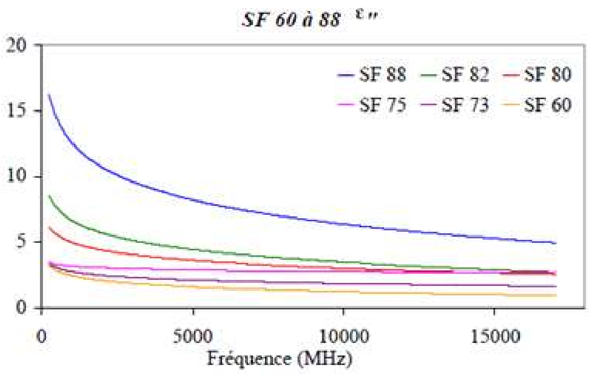
ALKARD SF

It is an absorbent based on filled silicones which is generally in the form of "rubberized" plates. The thickness is made on demand as well as the hardness. The cutting is easily done with the scalpel which makes it an ideal absorbent for the study laboratories.

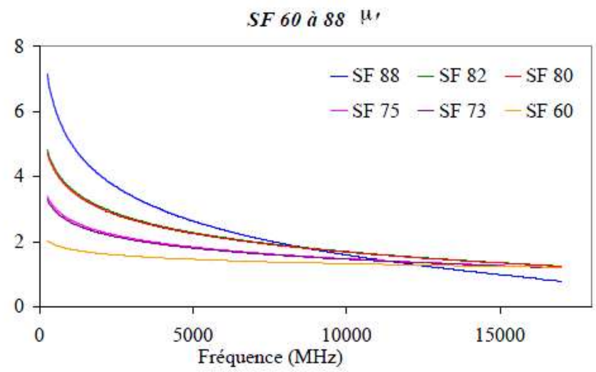
- **Presentation:** generally in the form of plates with thickness between 0.8 to 5mm (cutting on demand).
- **Composition:** silicones+iron+additives.
- **Utilization:** it can be placed externally to modify reflection conditions of certain objects or glued on complex shapes. It is often used to suppress clashes in microwave amplifiers, or to avoid leaks between two metal planes.

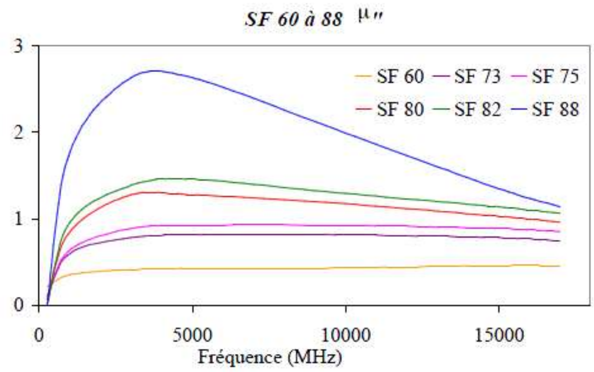
Electric permittivity vs frequency





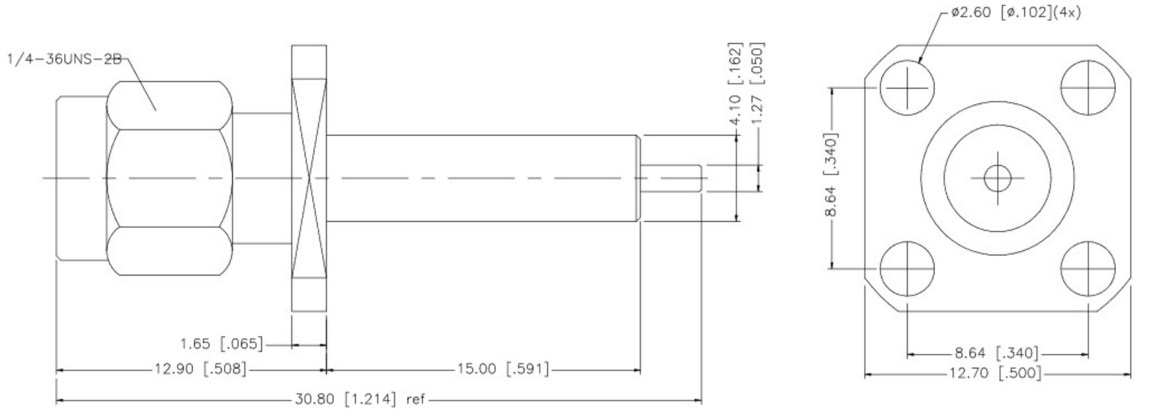
Magnetic permeability vs frequency





APPENDIX II

SMA HOLE PANEL RECEPTACLE PLUG



PANEL MOUNT PLUG RECEPTACLE - 4-HOLE SQUARE FLANGE - EXPOSED TFE TYPE					
P.N.	**Cable Group**	**Finish**	**Insulation**	**Impedance**	**Crimp Tool**
132144	N/A	Gold	Teflon	50	N/A
132300	N/A	Gold	Teflon	50	N/A
0.25mm central conductor, 3.17mm Teflon diameter					

https://www.amphenolrf.com/

APPENDIX III

Waveguide frequency bands and interior dimensions				
Frequency Band	Waveguide Standard	Frequency Limits (GHz)	Inside Dimensions (inches)	Inside Dimensions (mm)
	WR-2300	0.32 - 0.49	23.000 x 11.500	584.2 x 292.1
	WR-2100	0.35 - 0.53	21.000 x 10.500	533.4 x 266.7
	WR-1800	0.43 - 0.62	18.000 x 9.000	457.2 x 288.6
	WR-1500	0.49 - 0.74	15.000 x 7.500	381.0 x 190.5
	WR-1150	0.64 - 0.96	11.500 x 5.750	292.1 x 146.05
	WR-1000	0.75 - 1.1	9.975 x 4.875	253.365 x 126.6825
	WR-770	0.96 - 1.5	7.700 x 3.385	195.58 x 97.79
	WR-650	1.12 to 1.70	6.500 x 3.250	165.1 x 82.55
R band	WR-430	1.70 to 2.60	4.300 x 2.150	109.22 x 54.61
D band	WR-340	2.20 to 3.30	3.400 x 1.700	86.36 x 43.18
S band	WR-284	2.60 to 3.95	2.840 x 1.340	72.136 x 34.036
E band	WR-229	3.30 to 4.90	2.290 x 1.150	58.166 x 29.21
G band	WR-187	3.95 to 5.85	1.872 x 0.872	47.5488 x 22.1488
F band	WR-159	4.90 to 7.05	1.590 x 0.795	49.386 x 20.193
C band	WR-137	5.85 to 8.20	1.372 x 0.622	34.8488 x 15.7988
H band	WR-112	7.05 to 10.00	1.122 x 0.497	28.4988 x 12.6238
X band	WR-90	8.2 to 12.4	0.900 x 0.400	22.86 x 10.16
X-Ku band	WR-75	10.0 to 15.0	0.750 x 0.375	19.05 x 9.525
Ku band	WR-62	12.4 to 18.0	0.622 x 0.311	15.7988 x 7.8994
K band	WR-51	15.0 to 22.0	0.510 x 0.255	12.954 x 6.477
K band	WR-42	18.0 to 26.5	0.420 x 0.170	10.668 x 4.318

www.microwaves101.com