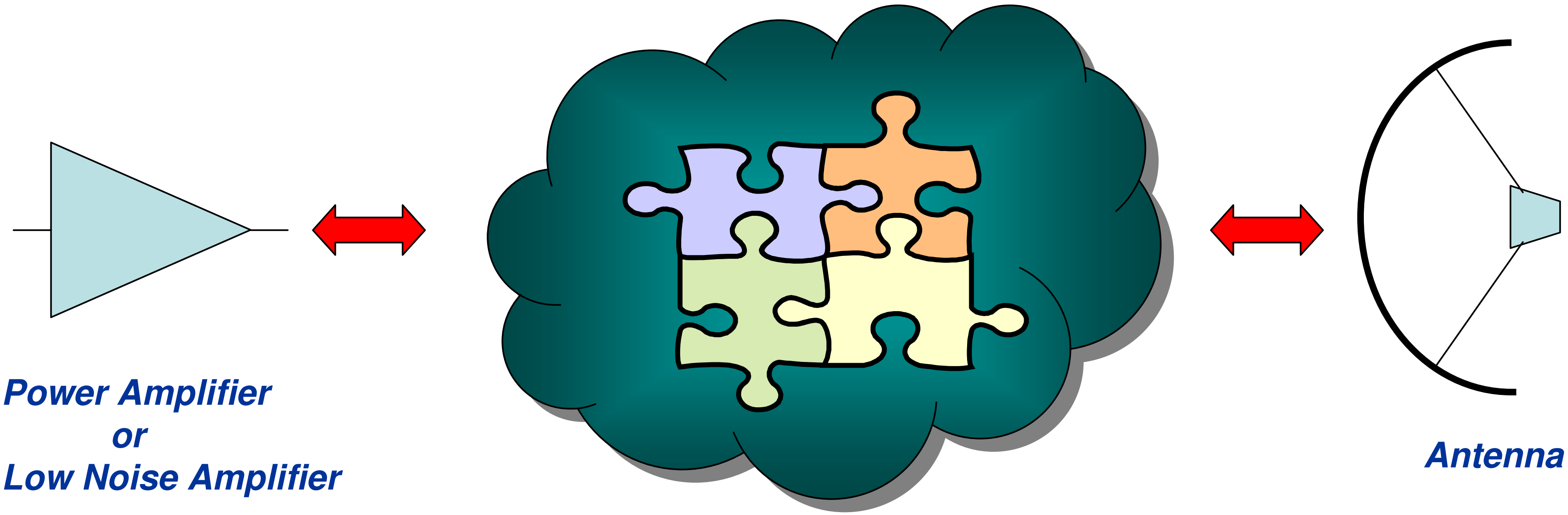
" Waveguide Subsystems for Antenna Feed"

Angel Mediavilla Sánchez*, Francisco Marante Rizo, Karen Cepero****

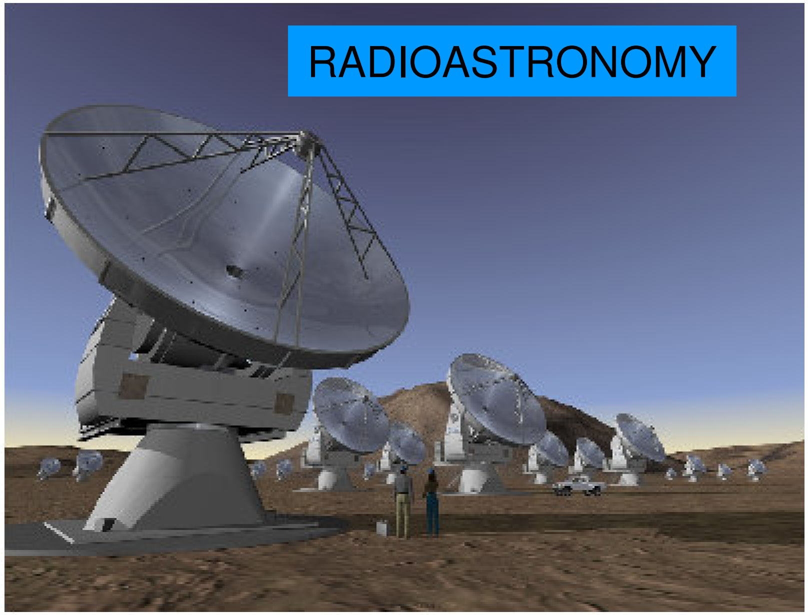
** Departamento de Ingeniería de Comunicaciones*
Escuela Técnica Superior de Ingenieros de Telecomunicación
Universidad de Cantabria (UNICAN) – España

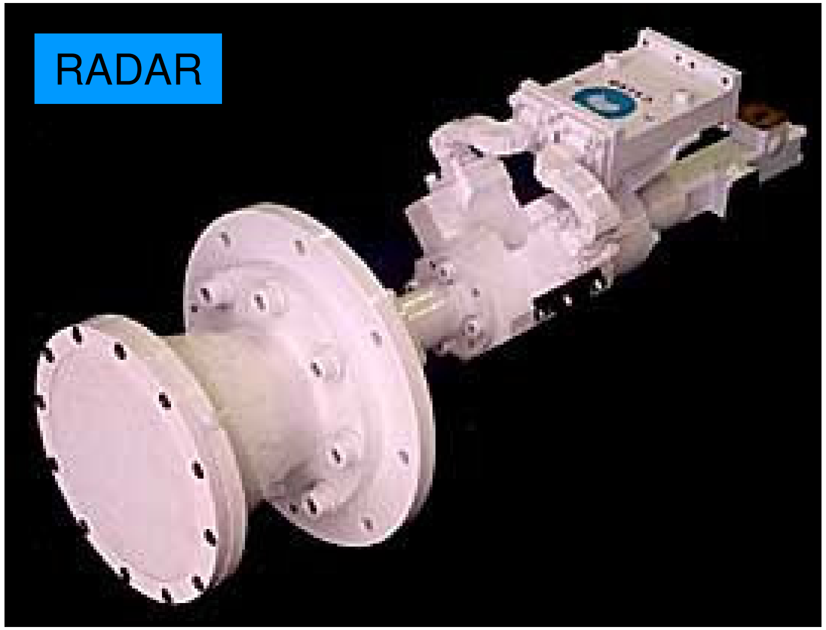
*** Departamento de Telecomunicaciones*
Instituto Superior Técnico José Antonio Echeverría (ISPJAE)
La Habana - Cuba

Where are we ?

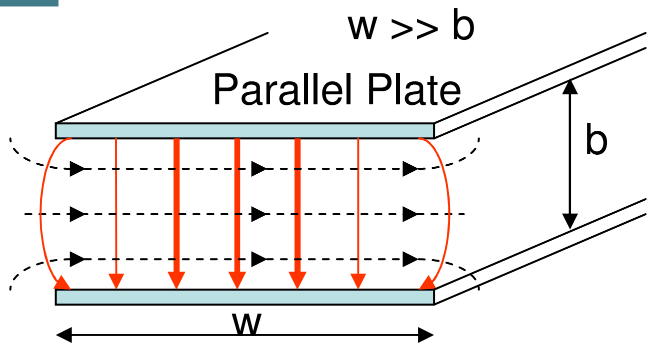


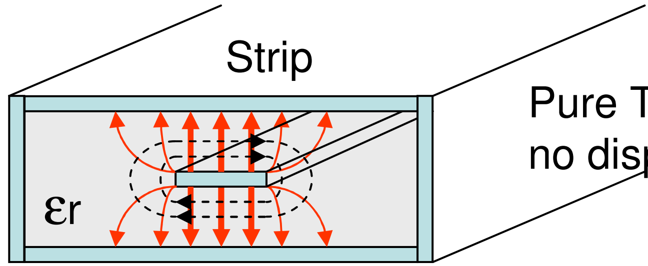
GENERALITIES



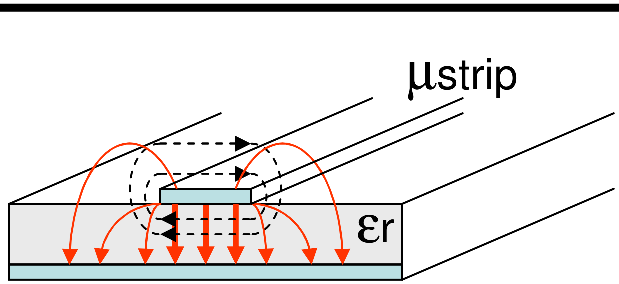


Bricolage also WORKS



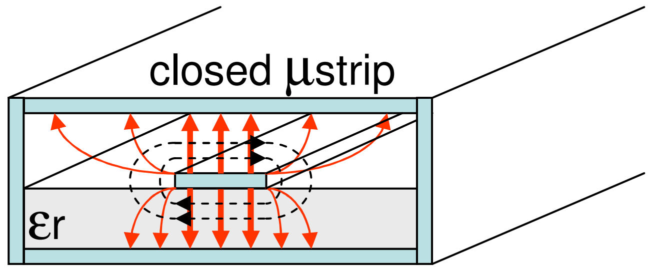


Pure TEM mode
no dispersion

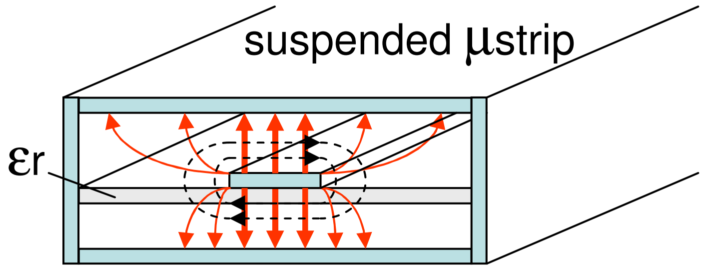


Important dispersion
Radiation Losses

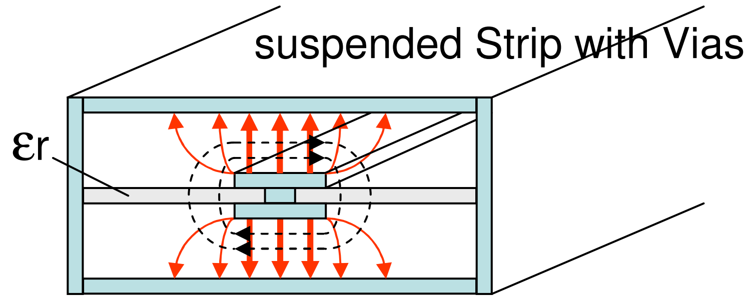
Propagate TEM or quasi-TEM



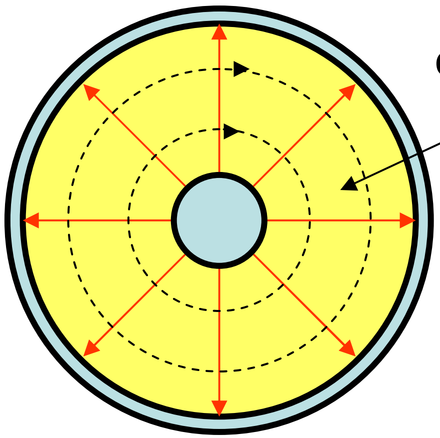
No radiation Losses
Waveguide modes could appear



Small Losses
In the dielectric



No dielectric Losses
No dispersion



$$Z_o = 60.(\mu r/\varepsilon r)^{0.5}.Ln(b/a)$$

$$vp = c / (\mu r.\varepsilon r)^{0.5} \Rightarrow \lambda = \lambda o.(vp/c)$$

$$\text{general: } \lambda g = \lambda o / (\varepsilon r)^{0.5}$$

Attenuation in dB/m: $\alpha = \alpha c + \alpha d$

$$\alpha c = 13.6 \frac{\delta s . (\varepsilon r)^{0.5}. [1 + b/a]}{\lambda o . b . Ln(b/a)}$$

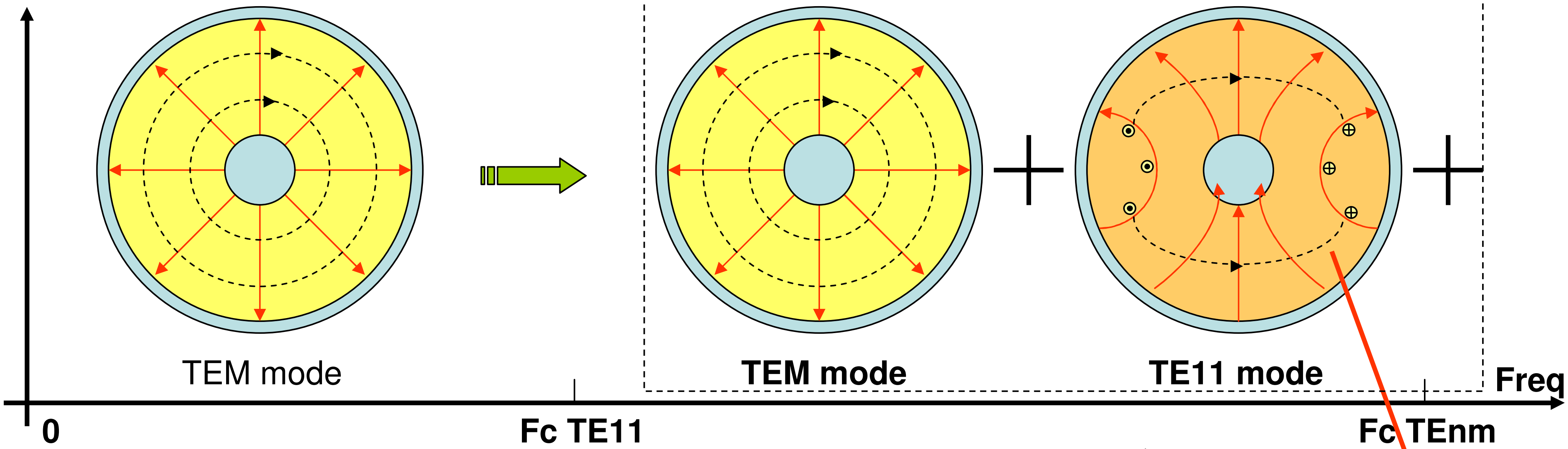
$$\alpha d = 27.3 \frac{(\varepsilon r)^{0.5}. \tan\delta}{\lambda o}$$

in db/m
- **δs** : Skin effect
- **tanδ** : dielectric

Both values increase with Frequency

If we **Increase** the transmission frequency

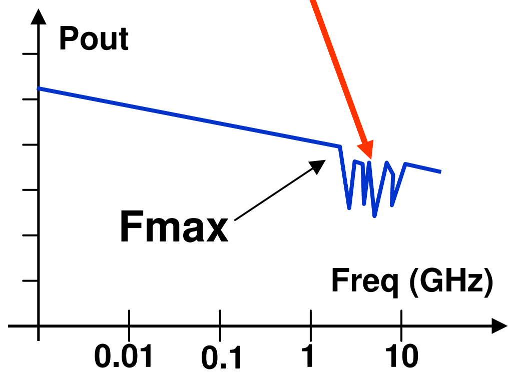
SUPERIOR modes



Nearest superior mode : TE11

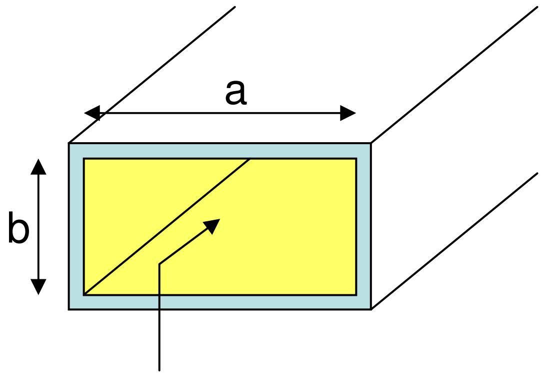
(for b/a < 7) **approximate** $\lambda_c = \pi.(a+b)$ → $F_c = \dfrac{c}{\pi\,(a+b)\,(\mu_r.\varepsilon_r)^{0.5}}$

Example : SMA connector 2b=4.1mm 2a=1.26mm Er=2.0
→ Zc=50ohm
Fc (TE11) = 25 GHz



Safely: Fmax=0.9Fc

Rectangular Waveguides



Multiple Modes
TEmn y TMmn
Depending on the working frequency

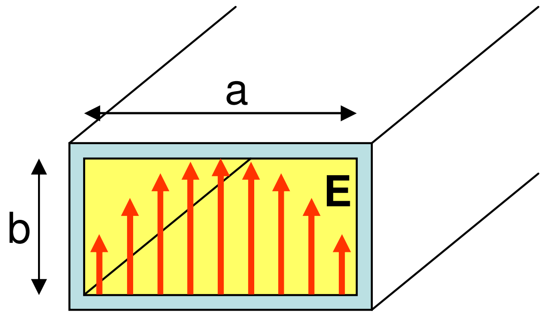
Usually a=2b

Standard Rectangular Waveguides

WR	BW TE10 (GHz)	Fc TE10 (GHz)	Power (MW)	Attn dB/33m	Dimensions axb (mm)	BAND
229	3.3-4.9	2.57	2	1	58.17x29.08	S
137	5.85-8.2	4.3	0.6	2.2	34.8x15.8	C
112	7.05-10.0	5.25	0.4	3	28.5x12.6	XI
90	8.2-12.4	6.55	0.25	4.8	22.86x10.16	X
62	12.4-18	9.48	0.12	5.4	15.8x7.9	KU
42	18-26.5	14.05	0.045	15	10.7x4.3	K
28	26.5-40	21.08	0.025		7.11x3.56	KA
22	33-50	26.34	0.016		5.7x2.8	Q
10	75-110	59.01	0.003		2.54x1.27	

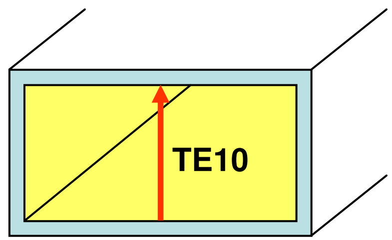
$Fc = c/2. [(m/a)^2+(n/b)^2]^{0.5}$
for TEmn on air

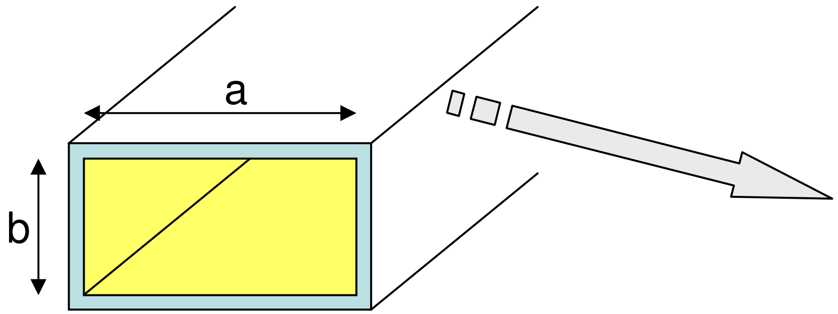
Cutoff Frequency TEmn



TE10 mode

BW TE10: 1.2FcTE10 y 1.9FcTE10

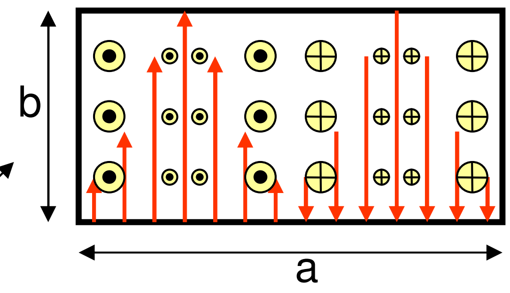




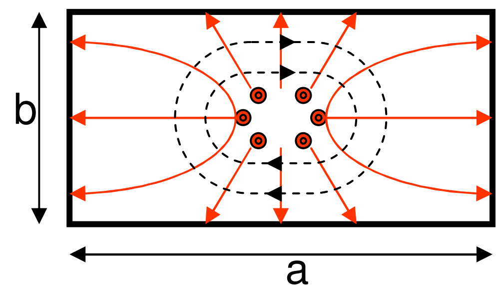
Example: WR90 (X band)
a=22.86mm
b=10.16mm

Mode	Fc(GHz)
TE10	6.557
TE20	13.114
TE01	14.753
TE11	16.145
TM11	16.145
TE30	19.671
TE21	19.739
TM21	19.739
TE31	24.589
TM31	24.589
TE40	26.228

TE20



TM11

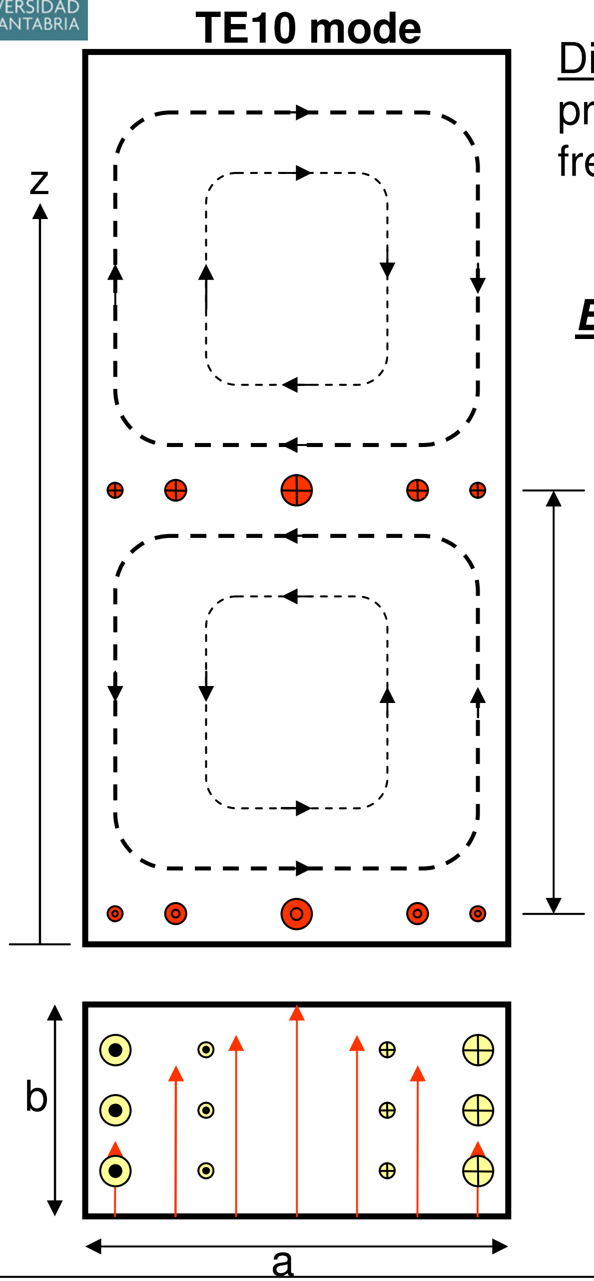


$F_c = c/2. [(m/a)^2+(n/b)^2]^{0.5}$
for TEmn

Cutoff Frequency TEmn

BW TE10: 1.2Fc10 y 1.9Fc10

BW=33%



Dispersive world: properties vary with frequency

Empty Waveguide

$\lambda c = c / Fc = 2.a$ Cutoff wavelength

$$\lambda g = \frac{\lambda o}{[1 - (\lambda o/\lambda c)^2]^{0.5}}$$ Guided wavelength

$\beta = 2\pi / \lambda g$ Prop. Constant

$Zc = 120\pi.(b/a).(\lambda g/\lambda o)$ Zc Power-Voltage

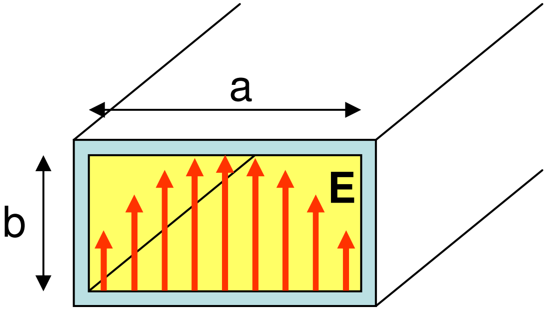
Waveguide Losses in dB/m:

$$\alpha d = \frac{27.3 \ \tan\delta}{\lambda o \ [1 - (Fc/F)^2]^{0.5}}$$

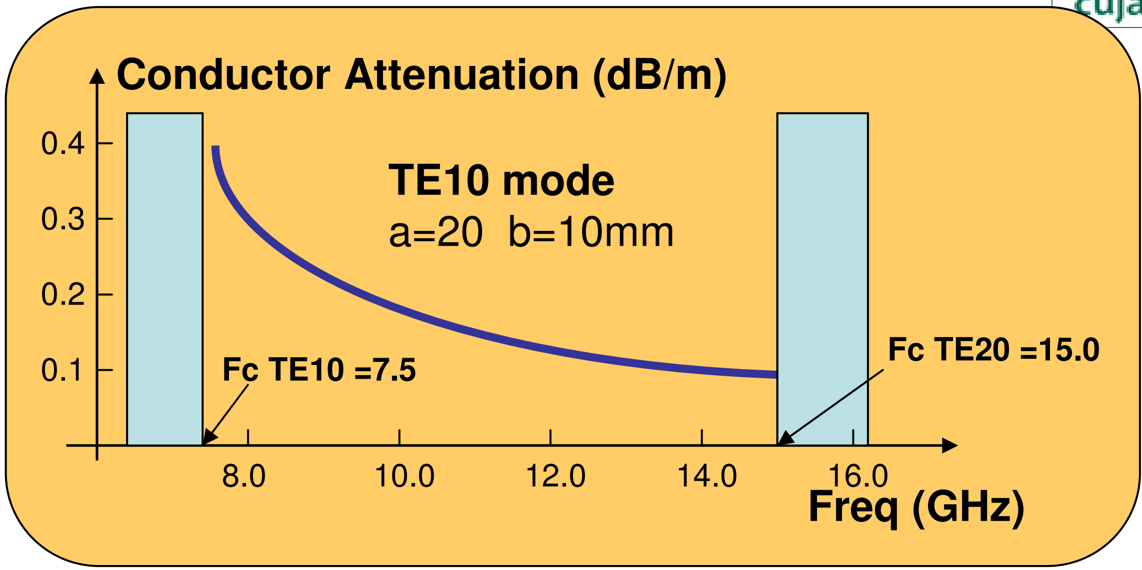
$$\alpha c = \frac{27.3 \ \delta s.[1+2b/a.(Fc/F)^2]}{\lambda o.b \ [1 - (Fc/F)^2]^{0.5}}$$

Empty Waveguide: only conductor losses, and they are Considerably lower with respect to a coaxial

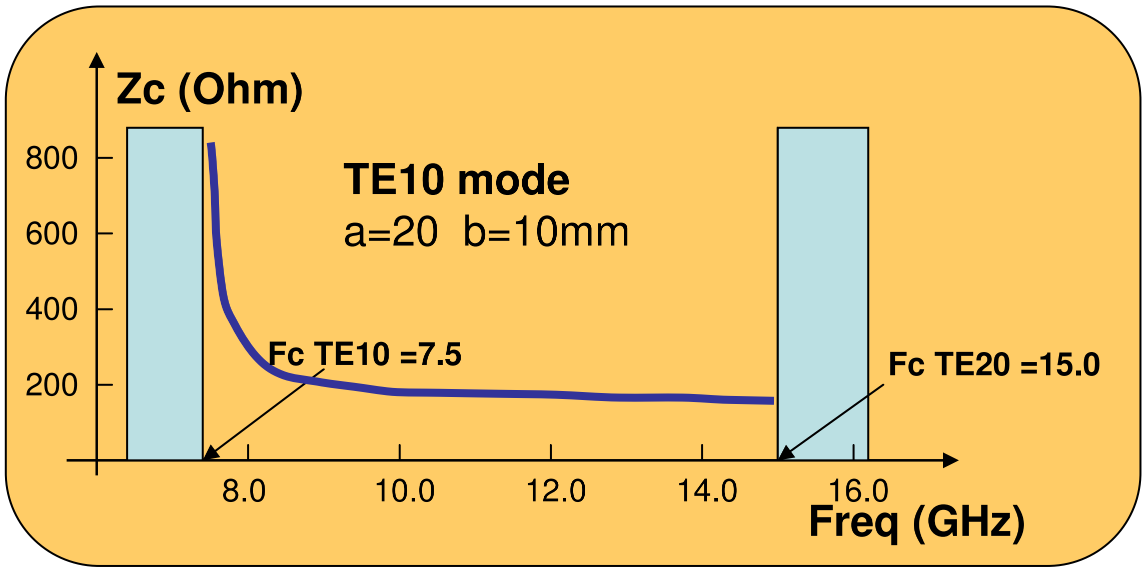
Rectangular waveguide works like a ***High-Pass FILTER*** . Cutoff frequency is the mode cutoff.

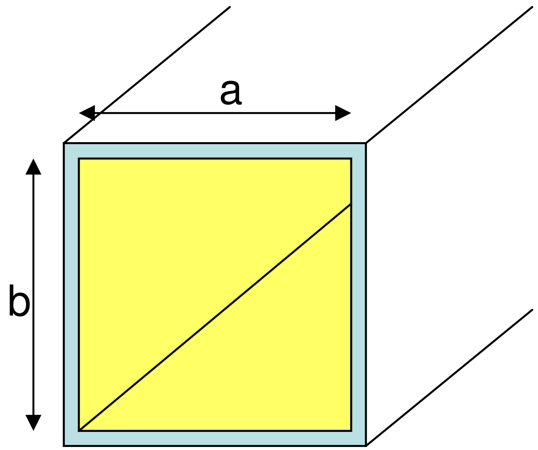


TE10 mode



Highly Dispersive Transmission Line





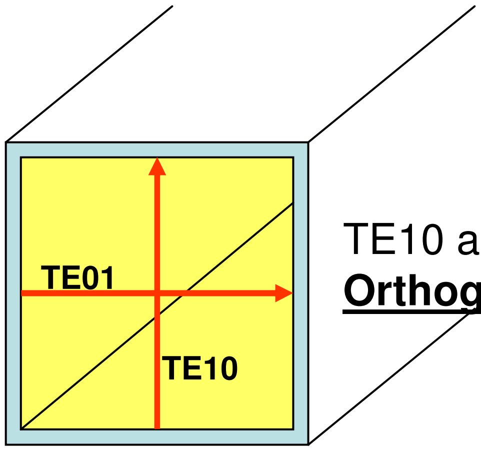
$Fc = c/2. [(m/a)^2+(n/b)^2]^{0.5}$ para TEmn

Cutoff frequency TEmn

a = b → FcTEmn=FcTEnm
FcTMmn=FcTMnm

Example: a = b = 14.6mm

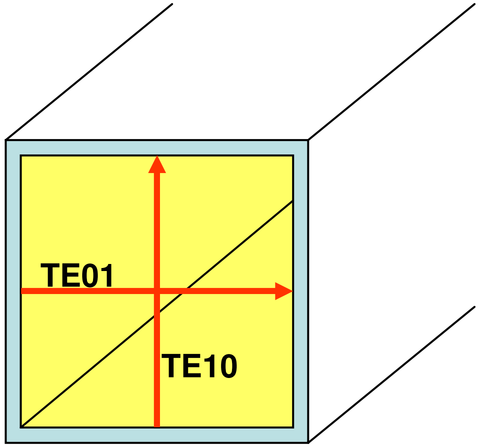
Mode	Fc(GHz)
TE10	10.266
TE01	10.266
TE11	14.519
TM11	14.519
TE20	20.533
TE02	20.533
TE21	22.957
TE12	22.957
TM21	22.957
TM12	22.957



TE10 and TE01 are **Orthogonal modes**

BW 10.26 y 14.5GHz

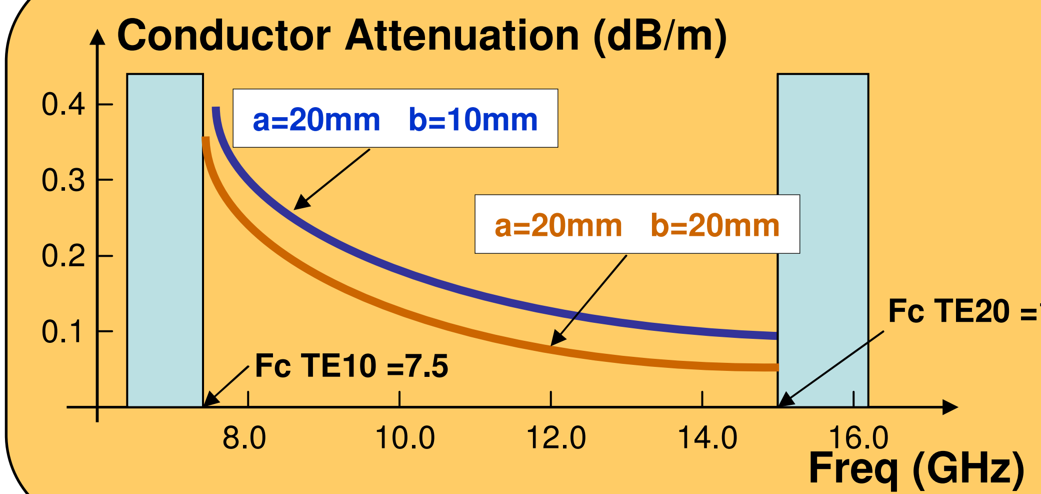
BW=17%



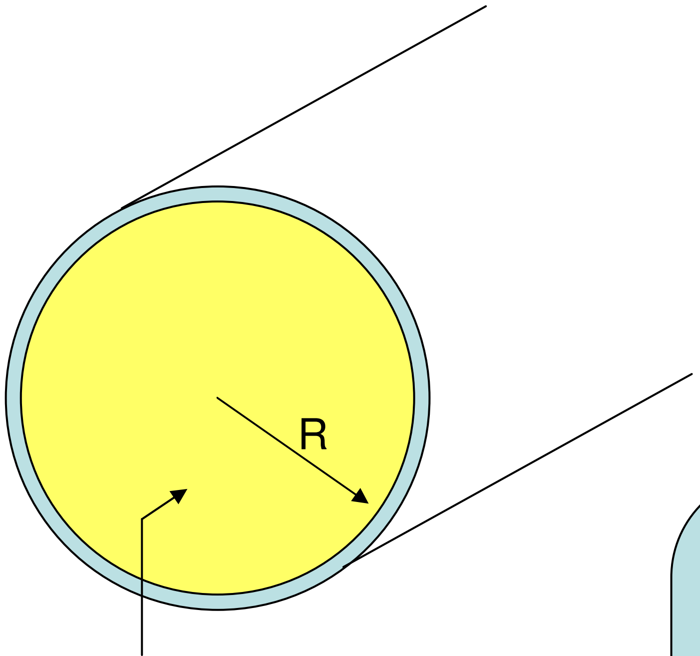
TE10 and TE01 are **orthogonal modes**

Conductor attenuation in SQUARE waveguide is lower than in RECTANGULAR waveguide

TE10 mode



CIRCULAR Waveguides



- Cutoff Frequencies: BESSEL functions

- Lower mode **TE11**: $\lambda c = 3.412$ R

- immediate superior mode **TM01** : $\lambda c = 2.612$ R

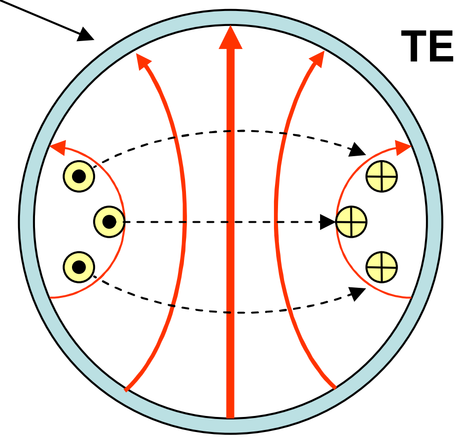
- Can support DUAL polarization: <u>Two orthogonal TE11 modes</u>

Multiple Modes
TEmn y TMmn
depending on the working frequency.

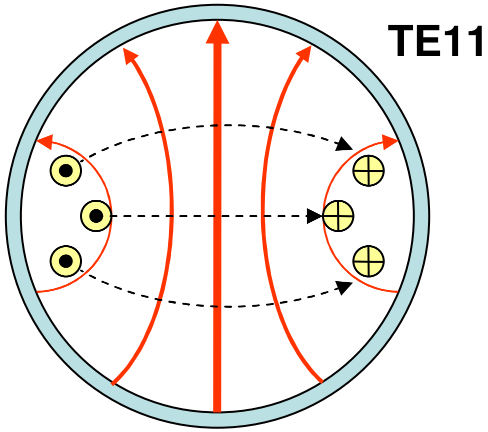
BW=13%

Example: R=11mm : C97

Mode	**Fc(GHz)**
TE11	7.98
TM01	10.43
TE21	13.25
TE01	16.62
TM11	16.62
TE31	18.22

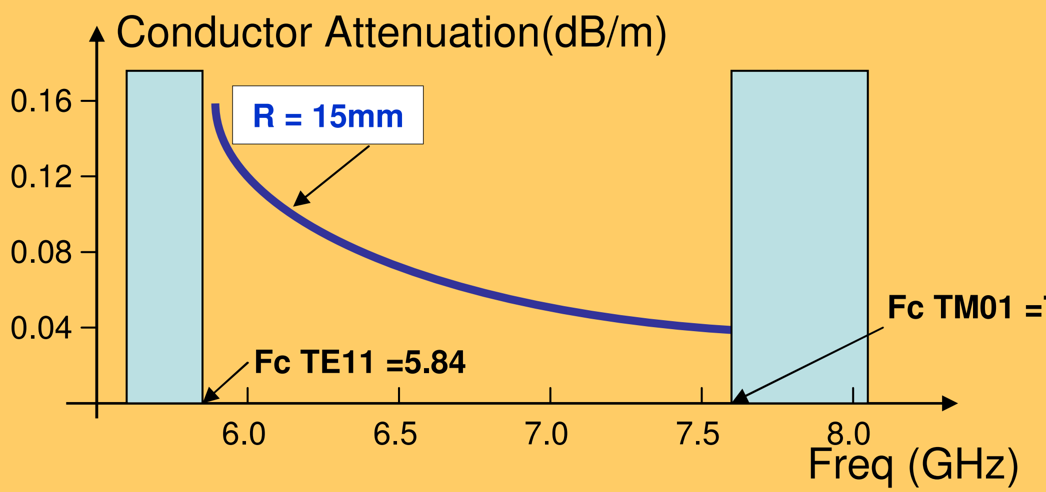


TE11

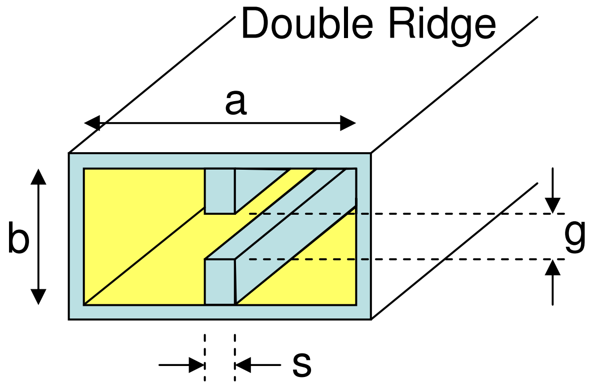


Losses are really lower than RECTANGULAR waveguides

TE11 mode

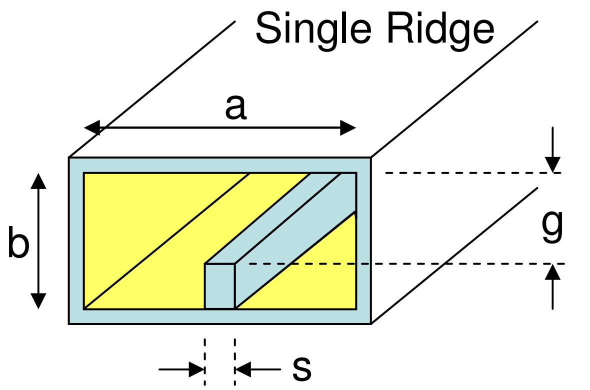


Very interesting for
Antenna feed systems



When using a ridge (single or double), the fundamental mode TE10 cutoff <u>decreases much more than the cutoff frequency of the next propagating mode</u> TE20.

→ **<u>Very broadband MONOMODE operation</u>**



<u>Example</u>: **Rectangular**
a=22.86mm b=10.16mm (WR90)

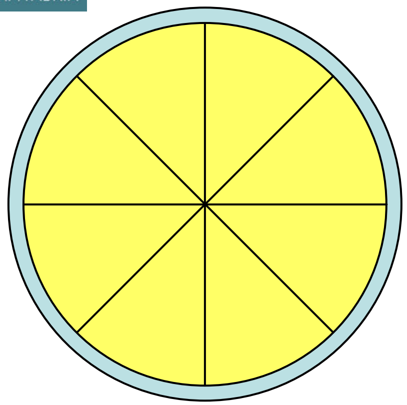
FcTE10 = 6.56GHz
FcTE20 = 13.11GHz

BW=33%

<u>Example</u>: **Single Ridge**
a=22.86mm b=10.16mm (WR90)
s=9.1mm g=2mm
FcTE10 = 3.125GHz
FcTE20 = 10.95GHz

BW=56%

Mode CUTTERS

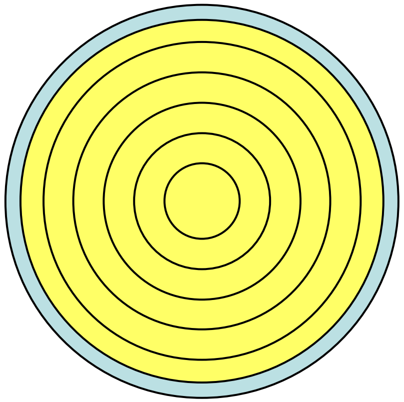


Circular Waveguide

Radial Wires :

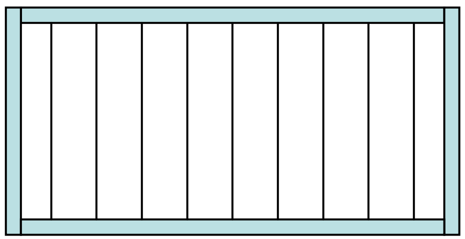
- Total reflection for the fundamental TE11 and all of TM
- Does not affect the circular modes TE01, TE02, … TE0n

- A given mode <u>PASS</u> if its **E** field is normal to the wires.
- If we want avoid reflection: Resistive elements



Circular wires supported by “foam”:

- Total reflection for all the TEmn modes
- Does not affect the immediate superior TM01 mode

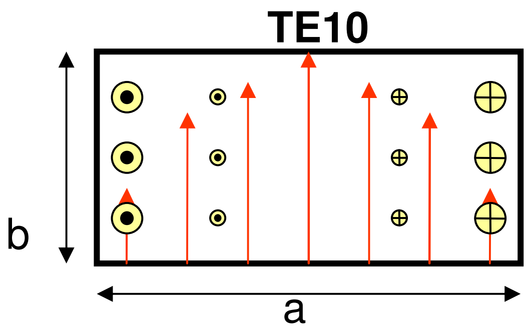


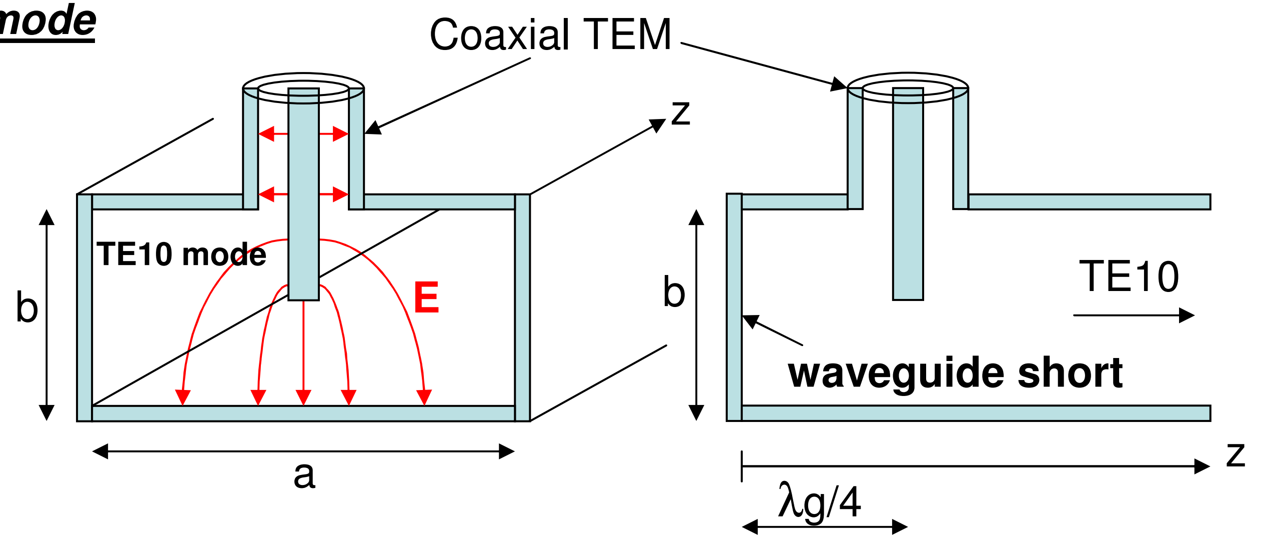
Rectangular Waveguide

Transversal wires :

- Total reflection for the fundamental TE10
- Total reflection for TE11 and all the TM modes
- Does not affect the possible TE01 mode.

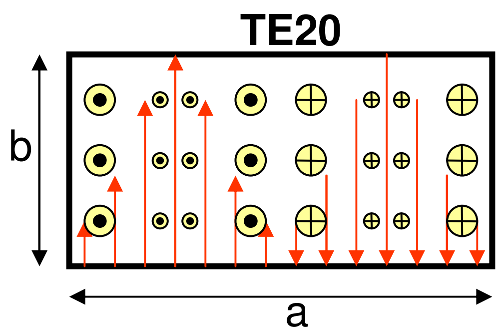
ELECTRICAL Probe to the TE10 mode

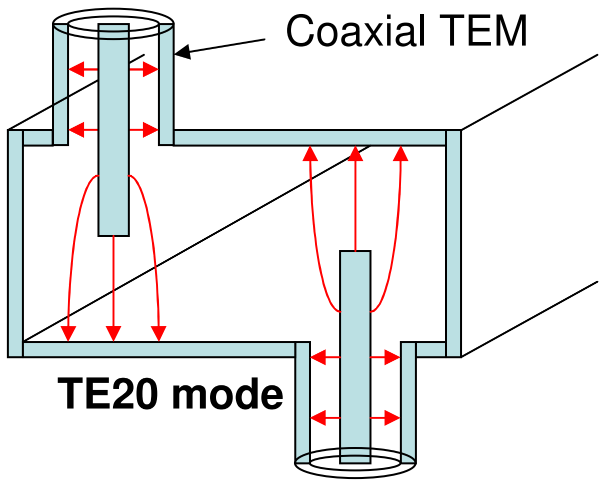




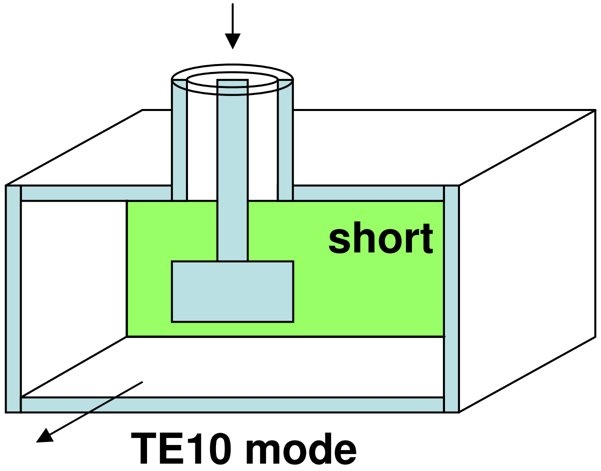
Electrical Probes to the TE20 mode

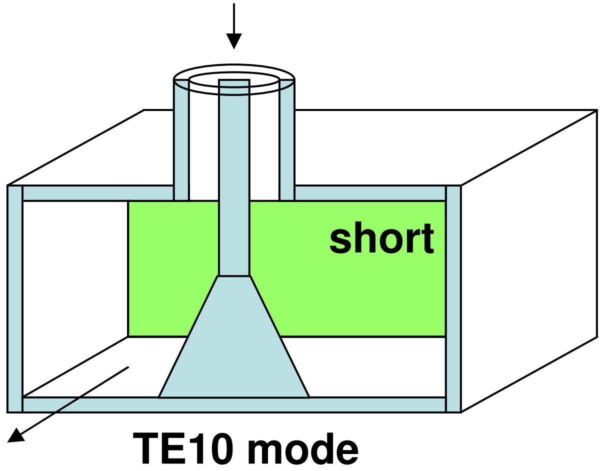
Signals in the two coaxial probes must be in phase.

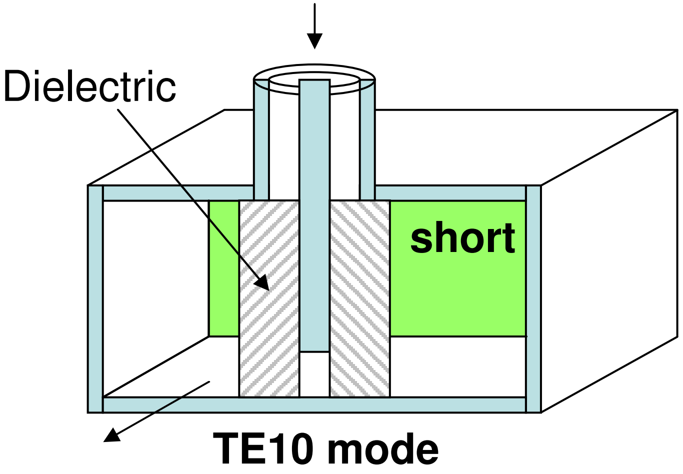




Different Improvements

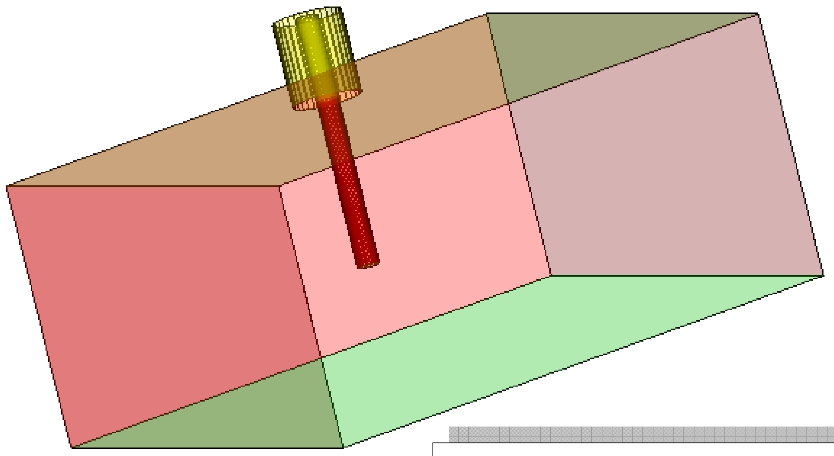


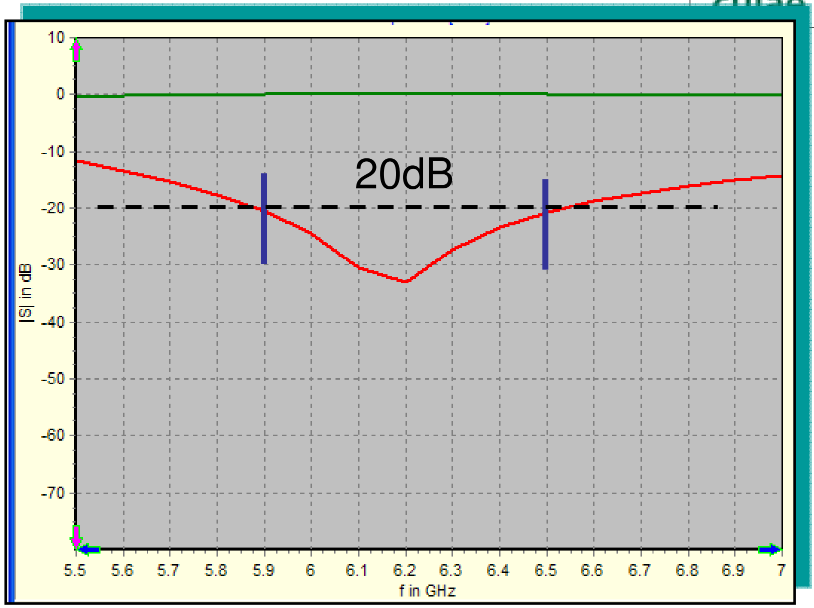




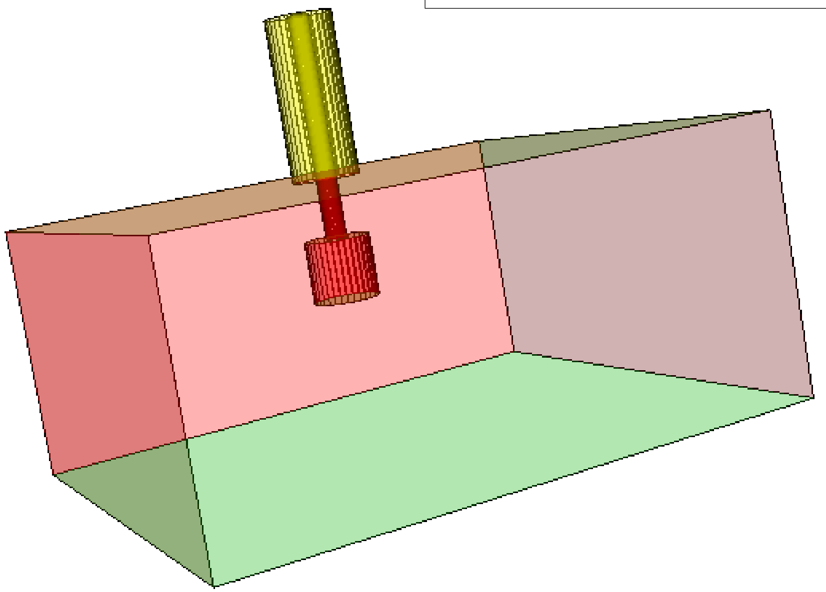
Broader Bandwidth

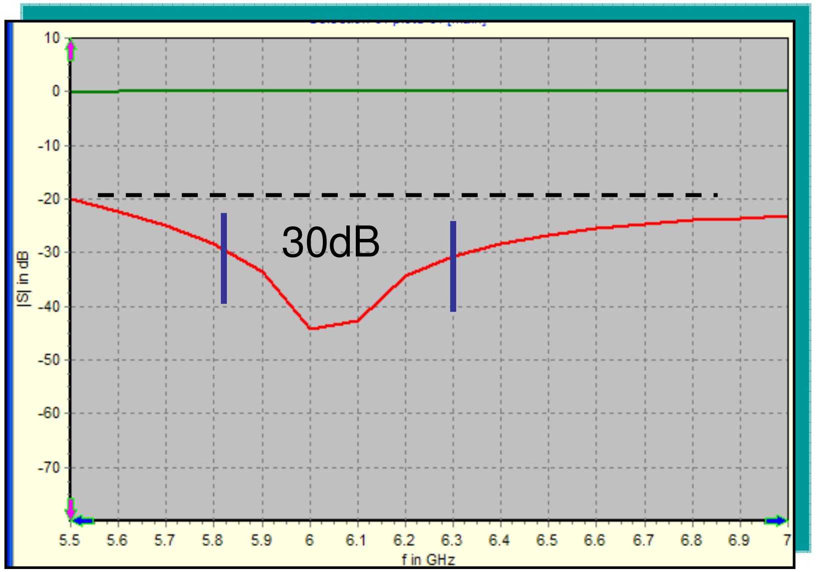
Rectangular-to-Coaxial Transducer



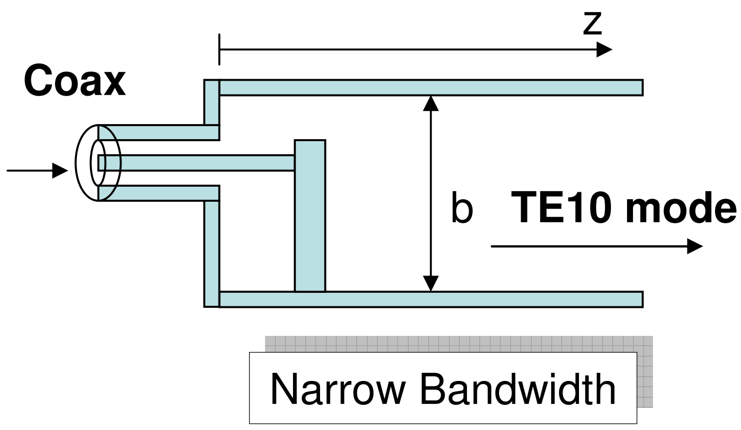


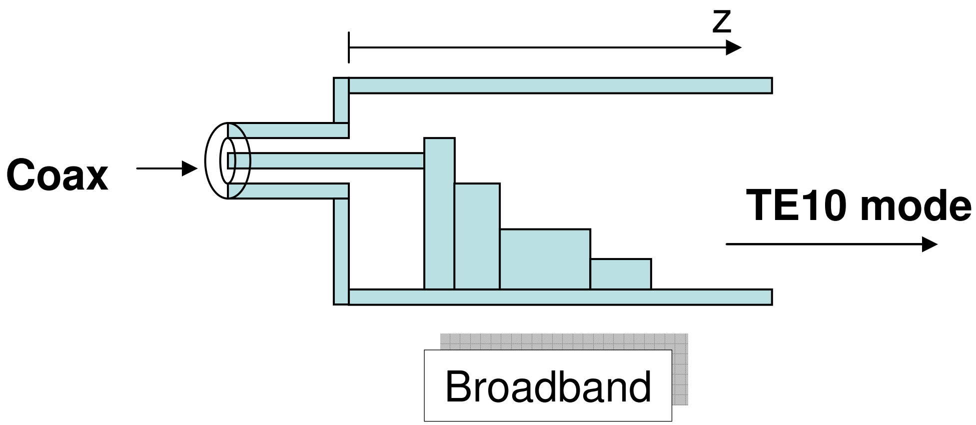
WR137: a=34.8 b=15.8mm
TE10: 5.5 a 8.1 GHz



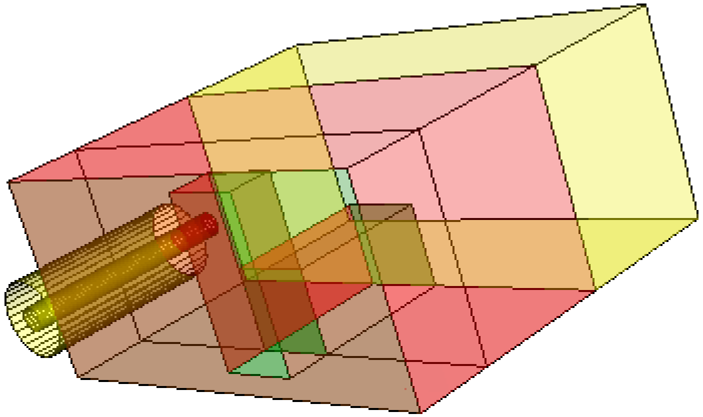


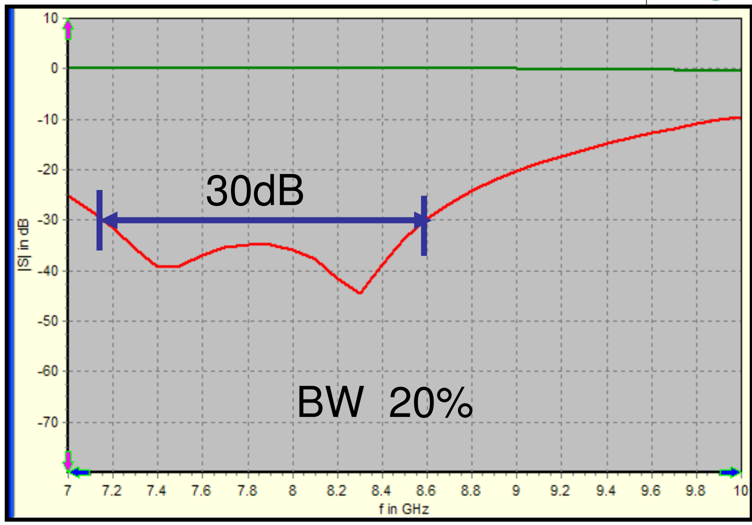
MAGNETIC Probe to the TE10



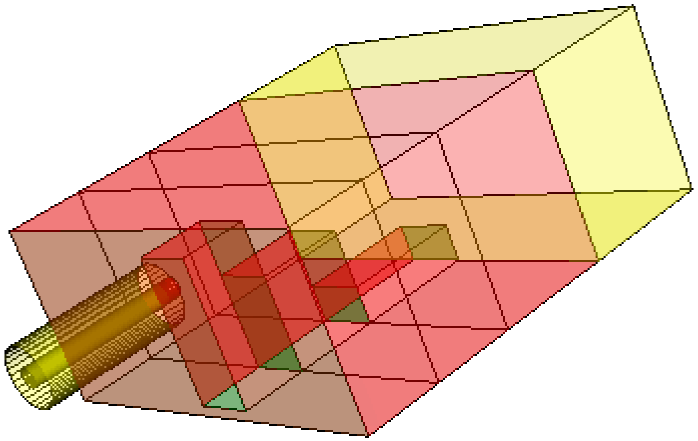


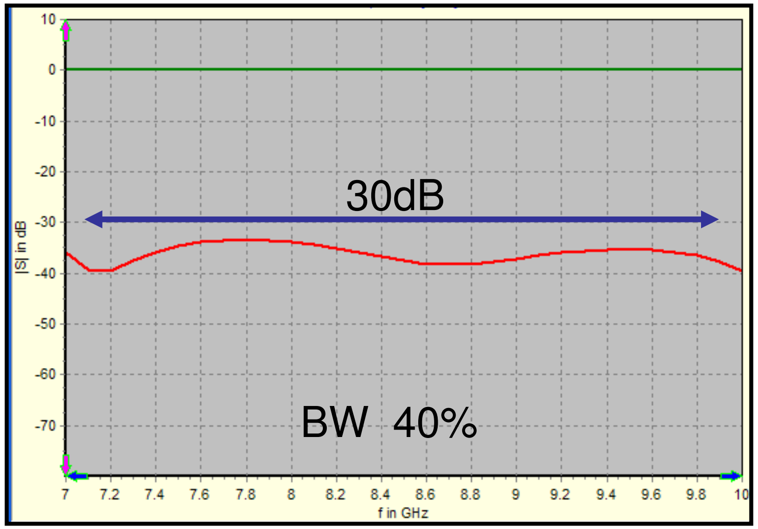
Rectangular-to-Coaxial Transducer





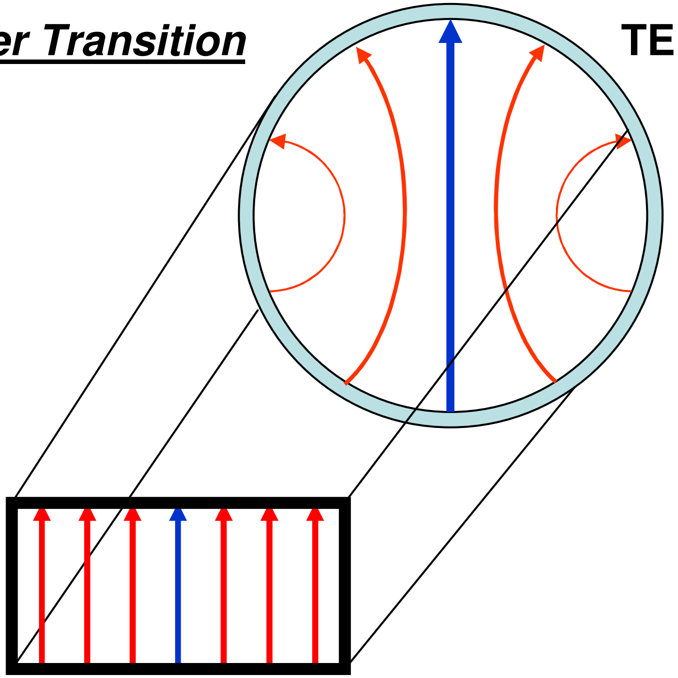
WR112: a=28.5 b=12.6mm
TE10: 6.5 a 10 GHz



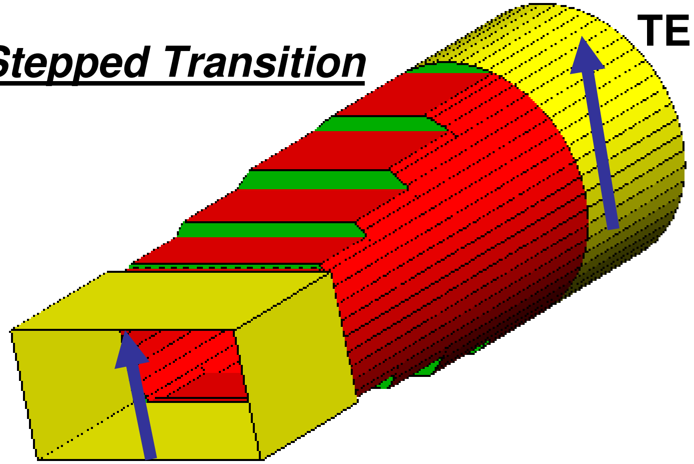


Rectangular-to-Circular Transducer

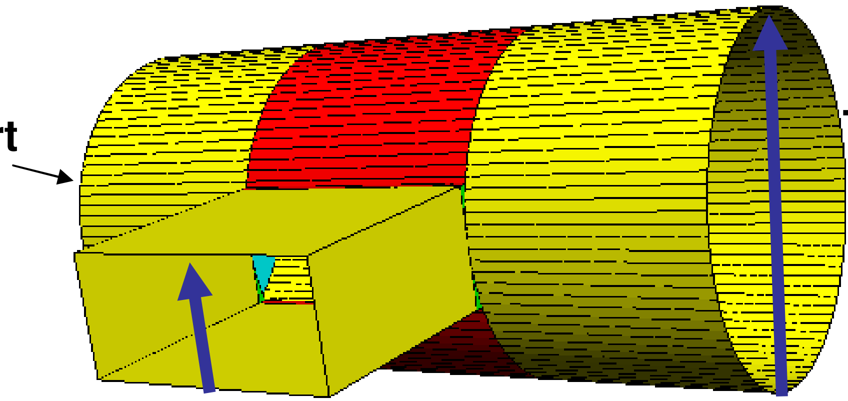
Taper Transition

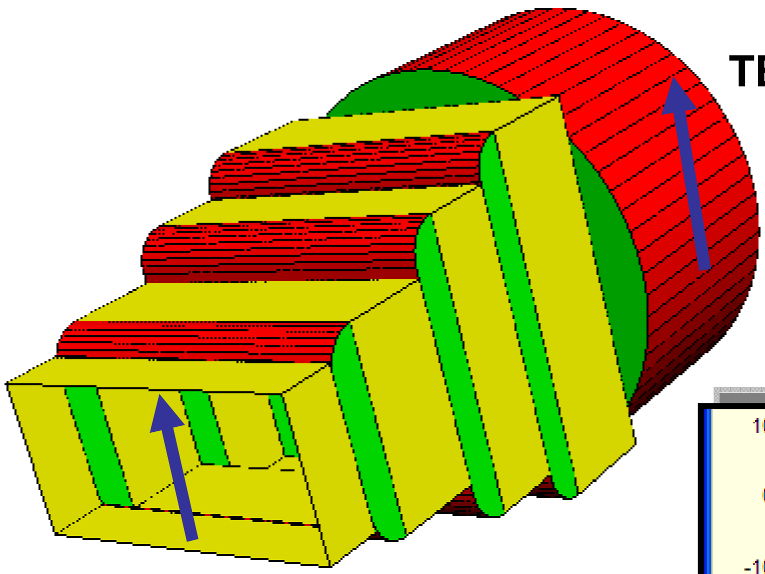


Stepped Transition



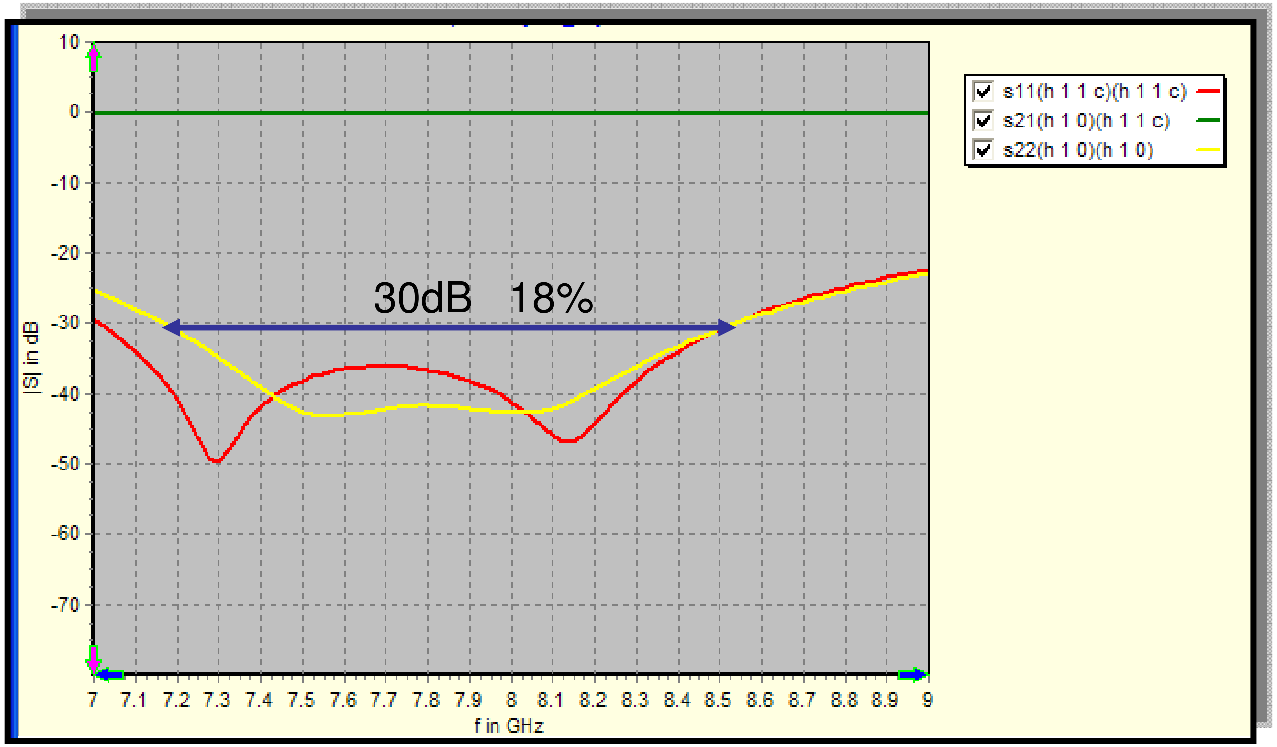
Perpendicular Transition



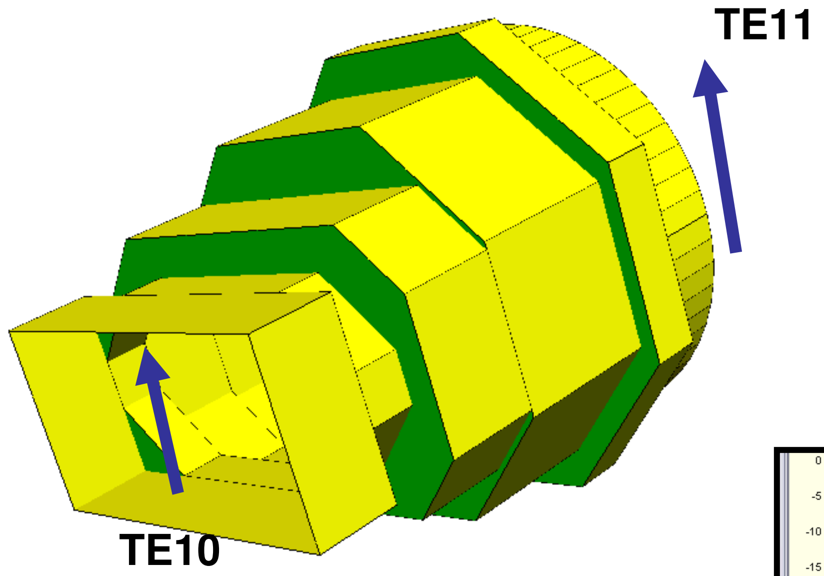


Stepped Transition

WR112: a=28.5 b=12.6mm
TE10: 6.5 a 10 GHz
BW@30dB : 18%

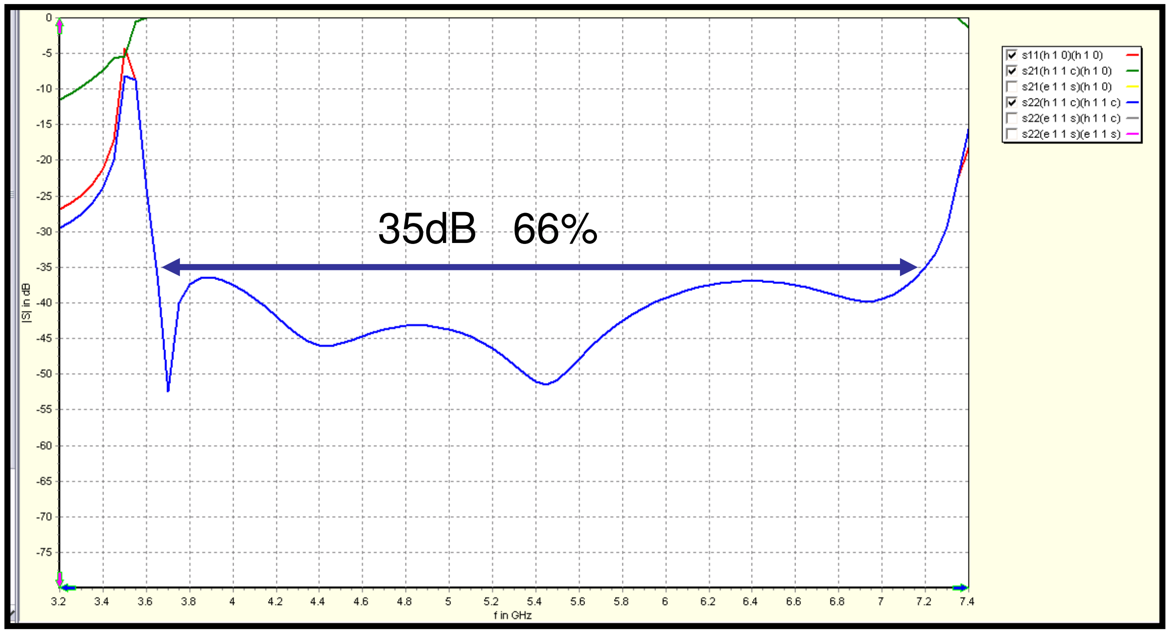


Rectangular-to-Circular Transducer

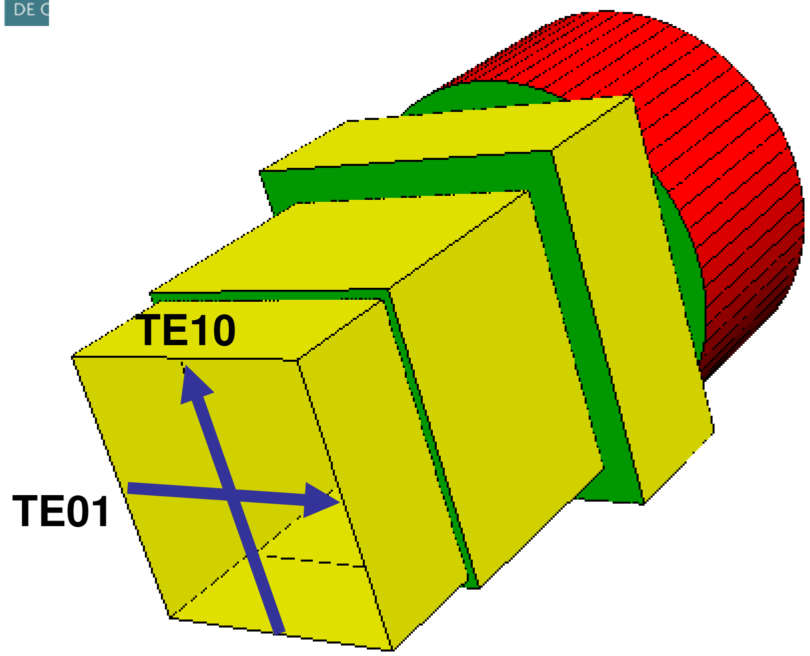


Stepped Transition
Using Intermediate Octagons

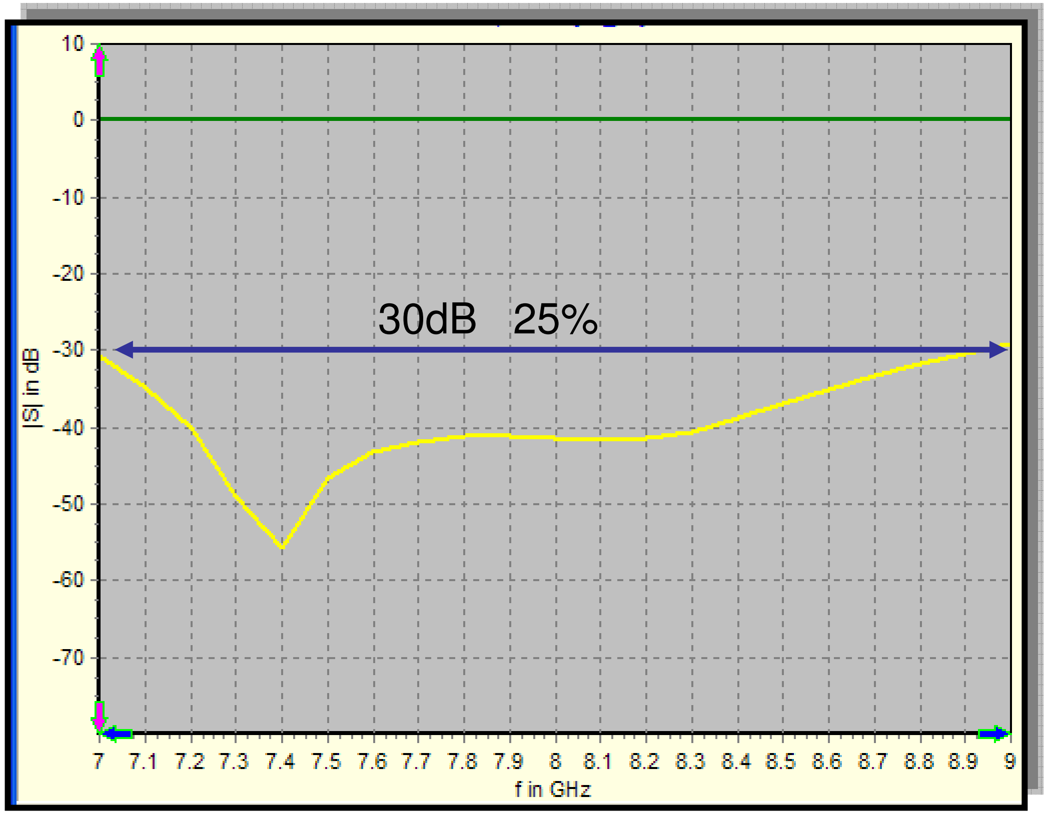
WR229: a=42.8 b=21.4mm
TE10: 3.6 a 7.2 GHz
BW@30dB : **66%**



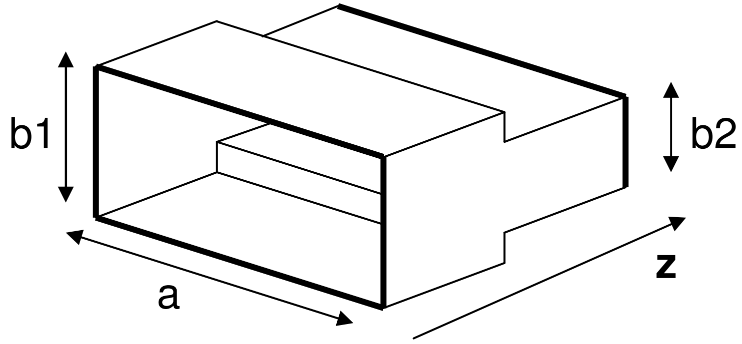
Square-to-Circular Transducer



BW@30dB : 25%



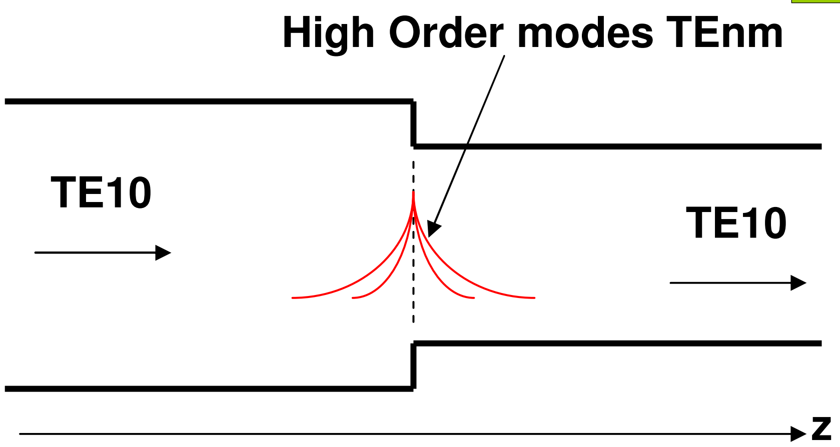
Step in Height

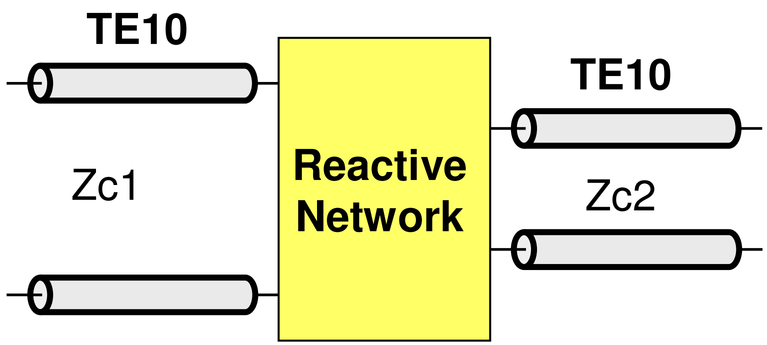


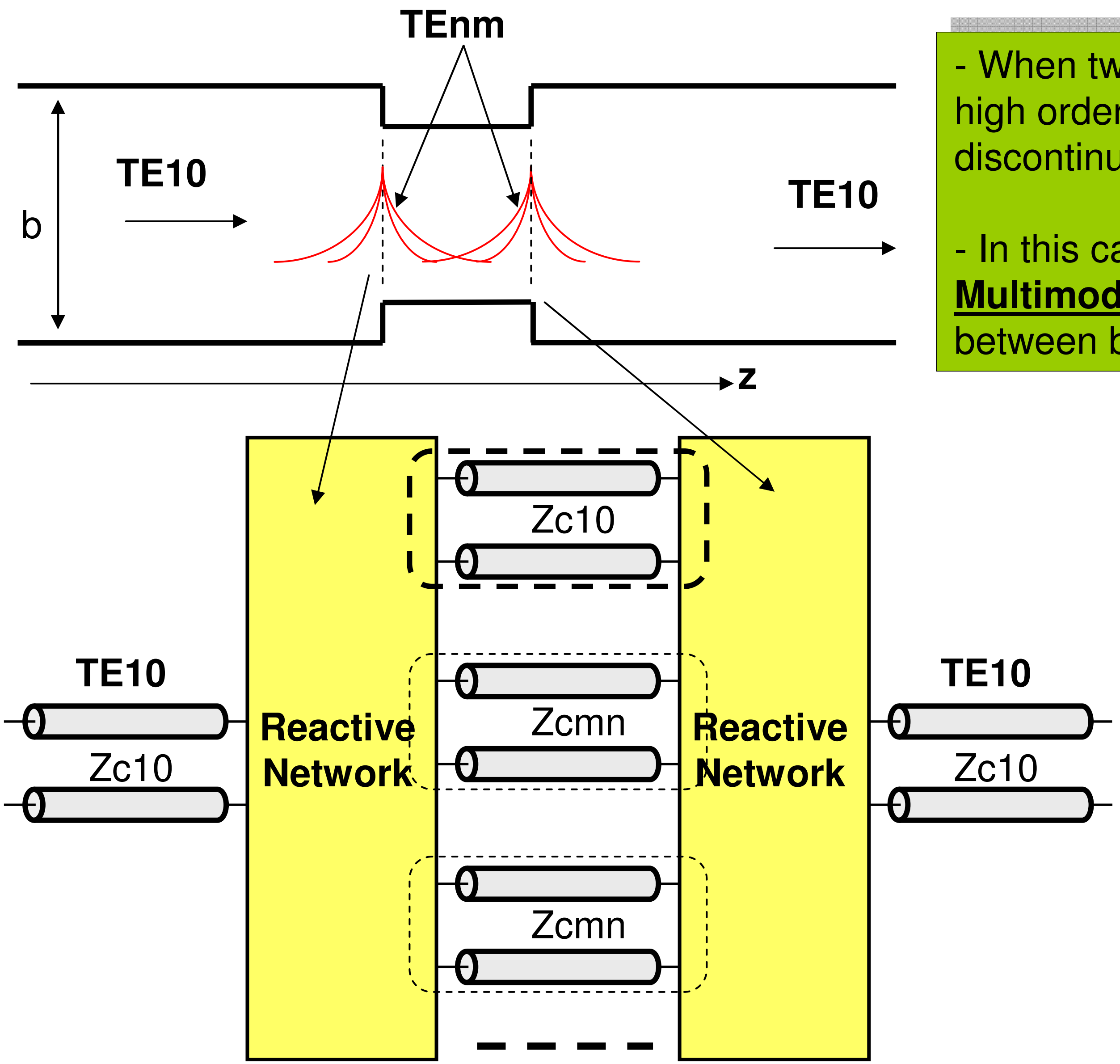
- We suppose to be operating in a frequency band where the **only propagating mode** is the fundamental one TE10

- At the discontinuity, high order modes are excited but they cannot propagate energy → They **store energy** acting as capacitors, inductors or combinations.

- They create a **reactive network**.





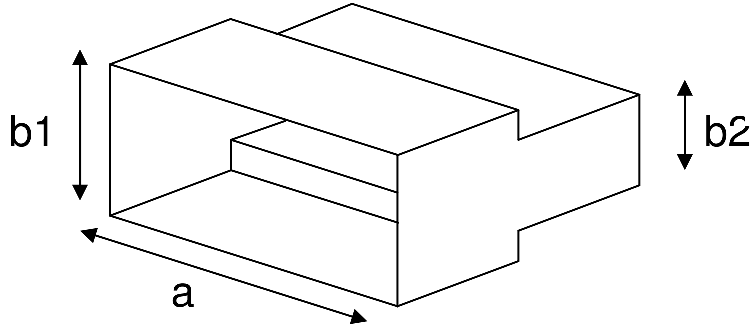


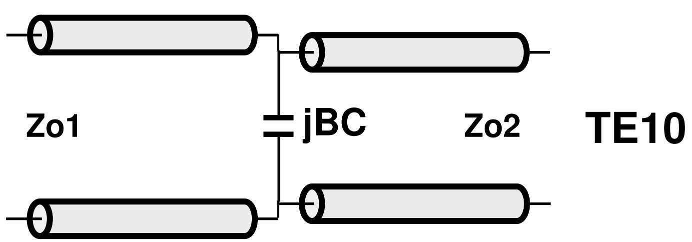
- When two discontinuities are close enough, high order modes may "**touch**" the second discontinuity.

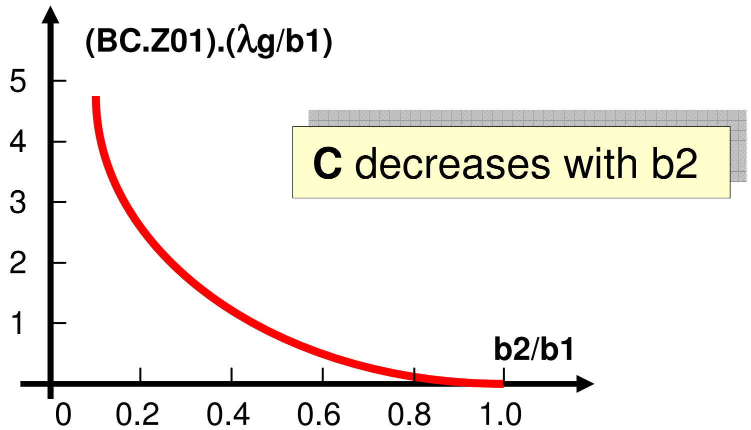
- In this case, the reactive networks are **Multimode** with mode-transmission-lines between both multi-ports.

Discontinuities in Rectangular Waveguides

E-Plane Step

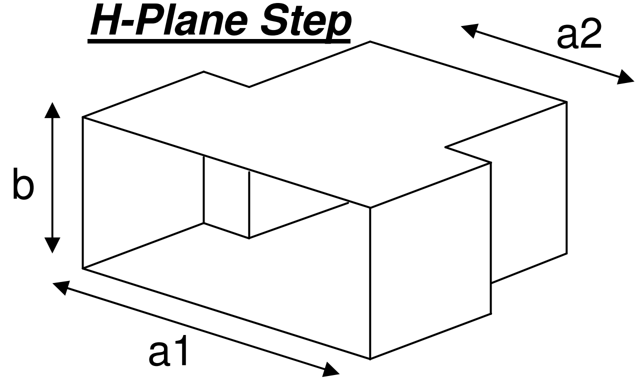


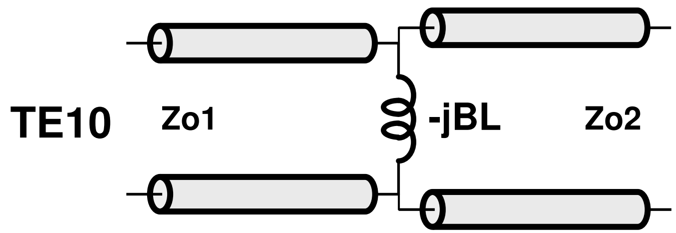


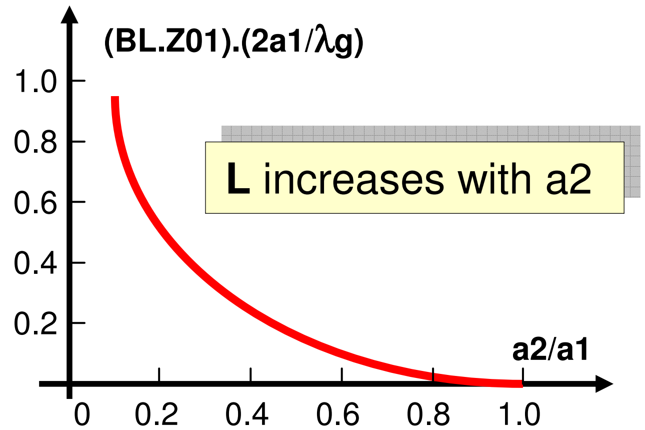


Steps are Useful for waveguide circuits

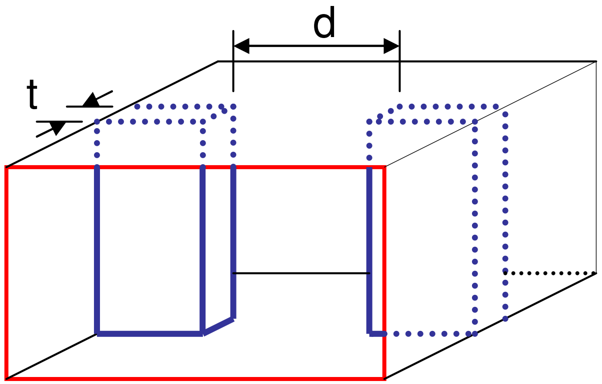
H-Plane Step



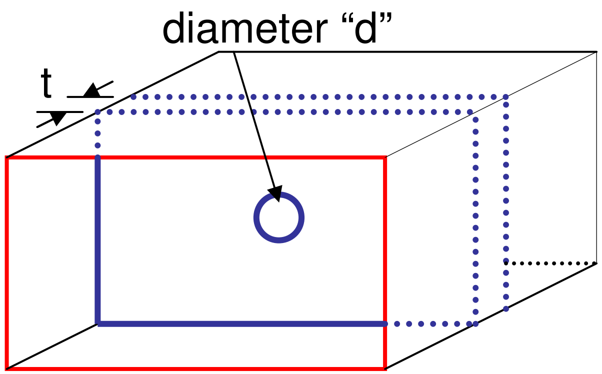




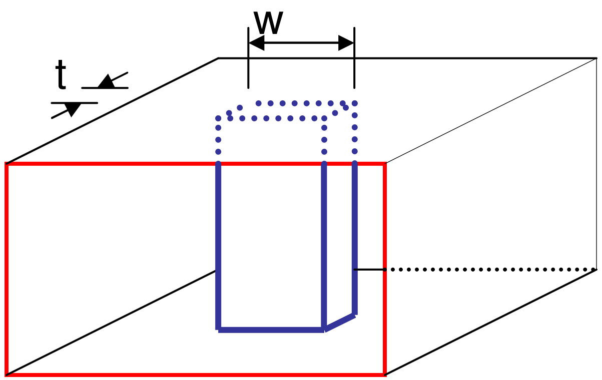
Discontinuities in Rectangular Waveguides



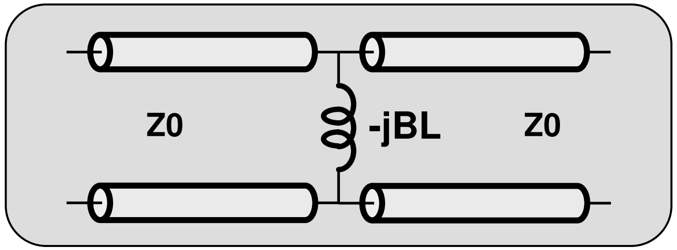
Iris-H symmetrical



Iris-circular

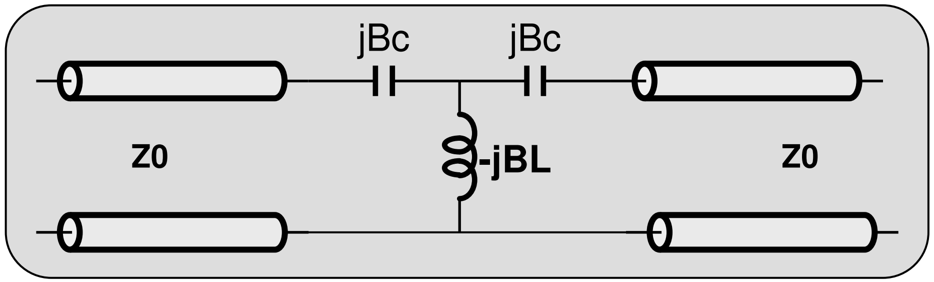


Fin-H plane



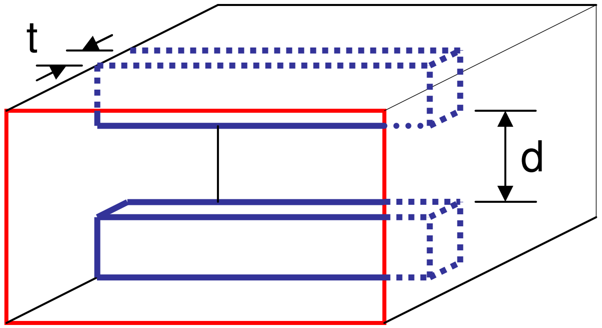
For small values of t → (t << a)

Useful for creating Waveguide Circuits

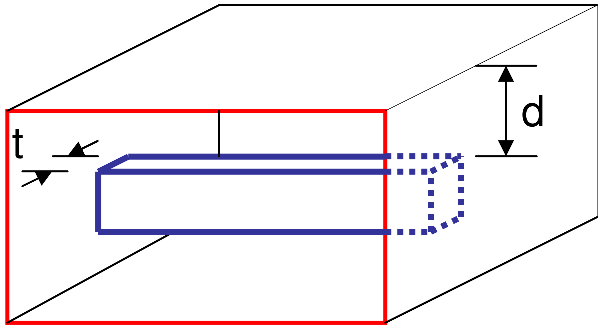


Additional Capacitors for higher values of "t"

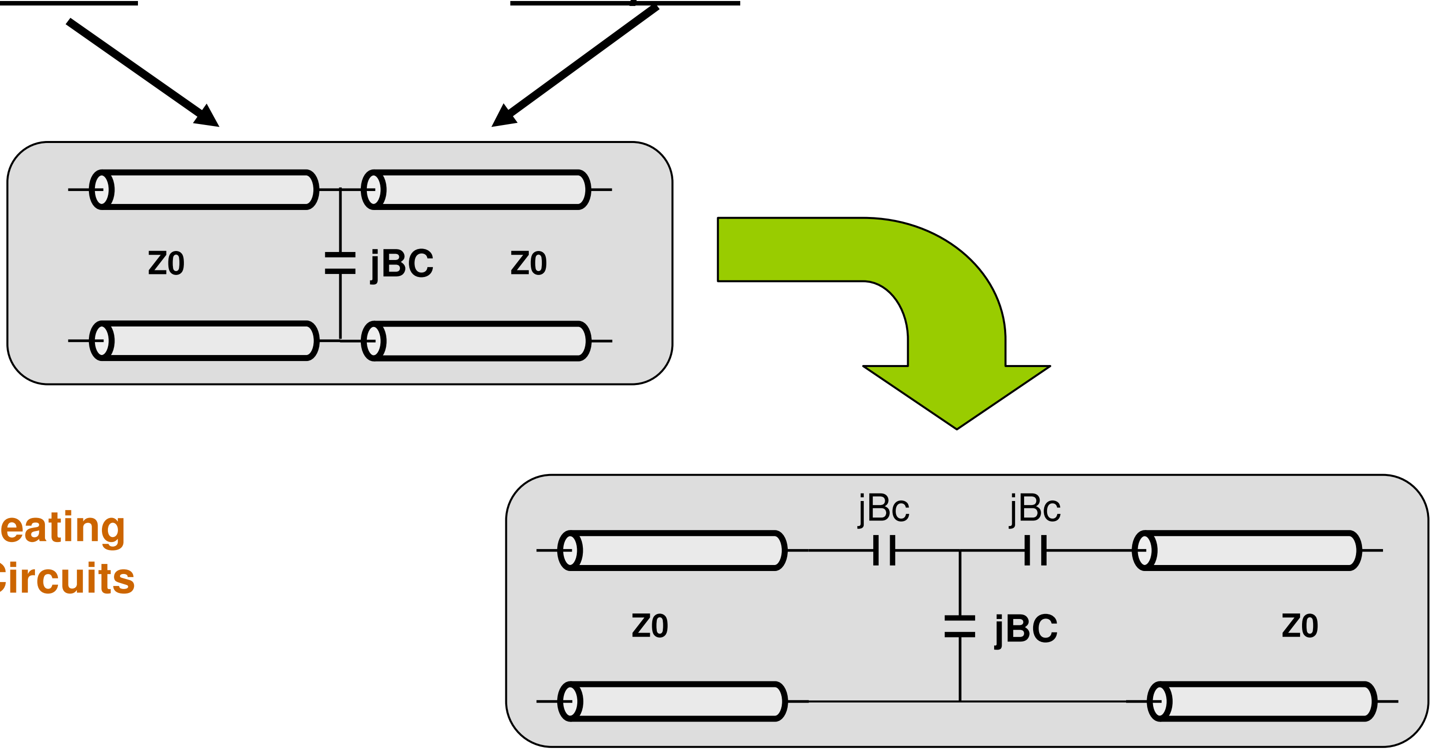
Discontinuities in Rectangular Waveguides



Iris-E symmetrical

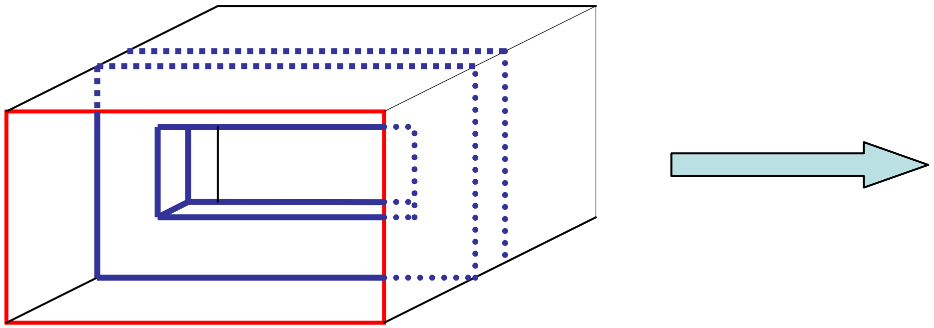


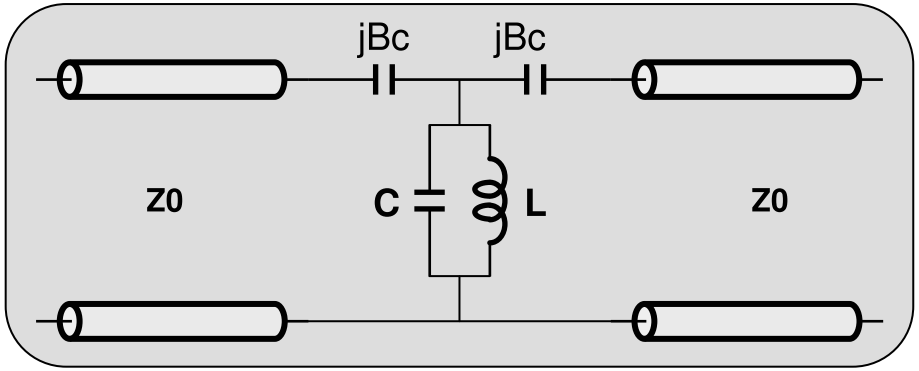
Fin-E plane



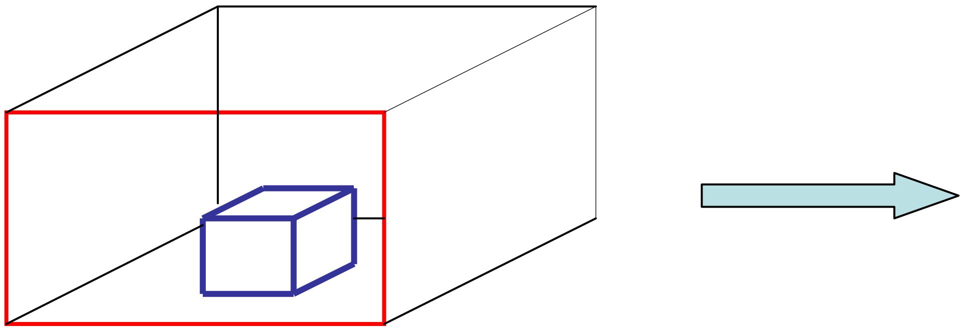
Useful for creating Waveguide Circuits

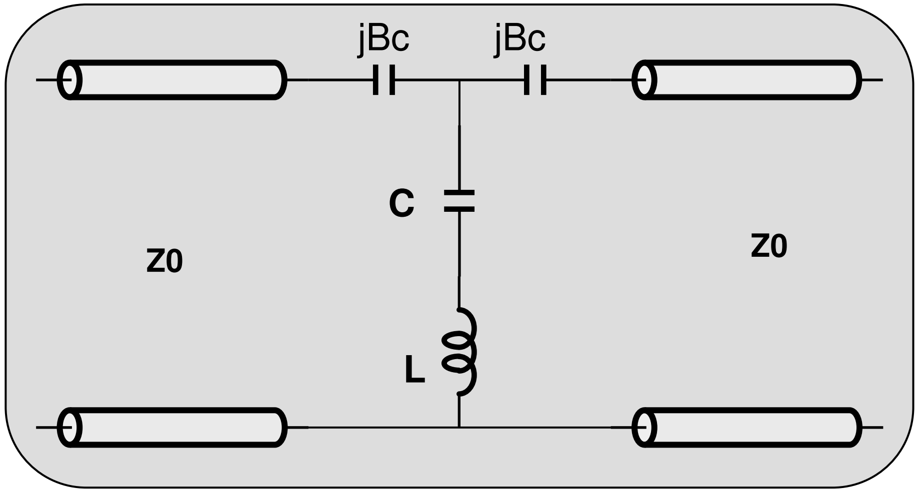
Discontinuities in Rectangular Waveguides





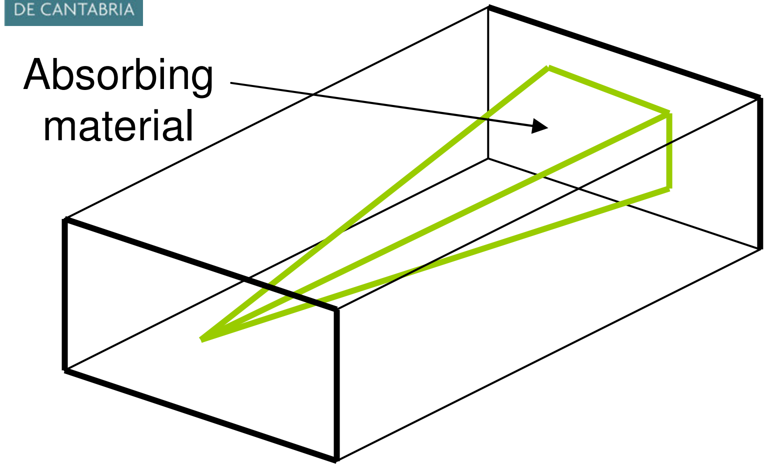
Resonant Iris



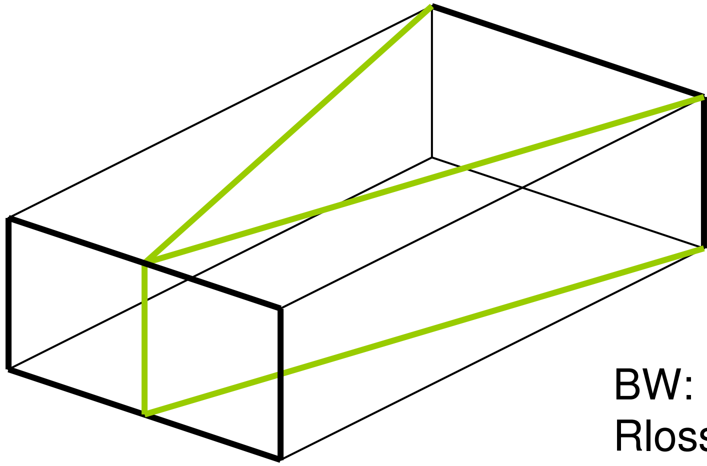


Post of variable height
(square or circular)

Matched Loads and Variable Shorts

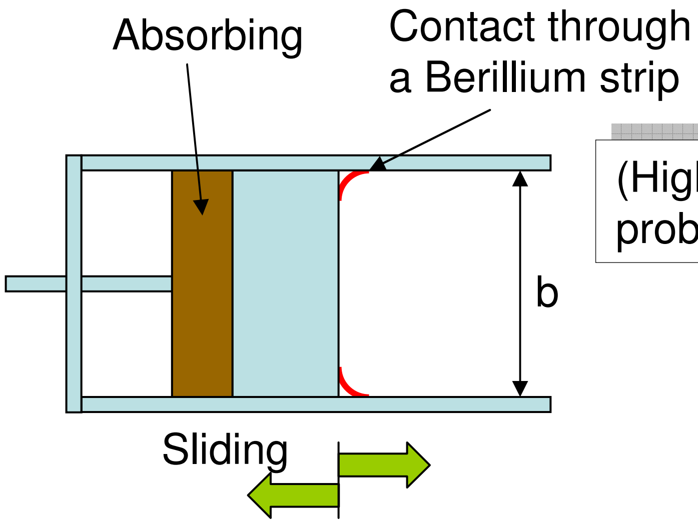


Termination for "low VSWR"

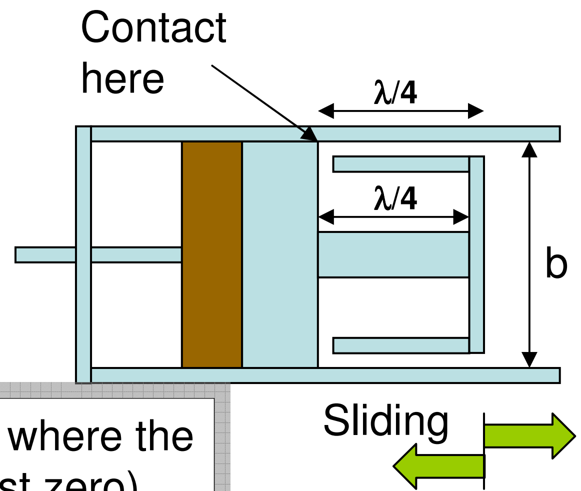


BW: Full band
Rloss 30-40dB

Termination for "High Power"



(High Frequency problems)

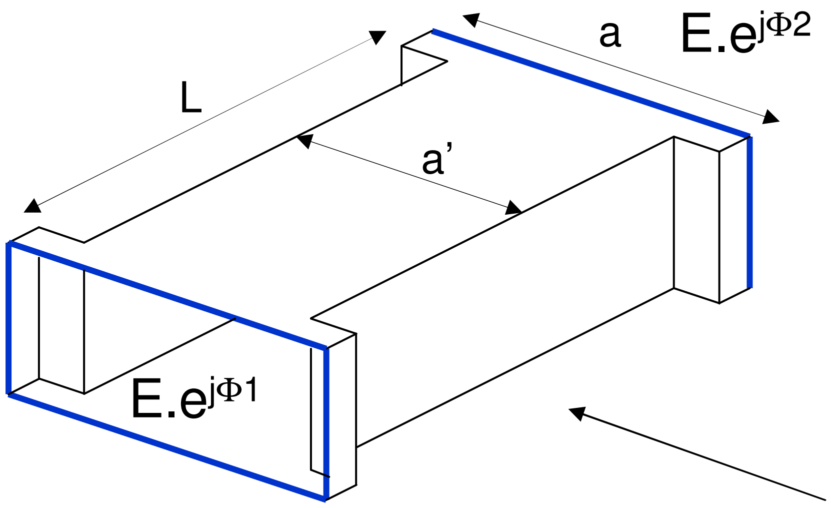


(Contact point: where the current is almost zero)

"Contacting" variable Short

"Non-contacting" variable Short

Differential Phase-Shifter "Narrow Band"



DPS by narrowing "a"

- En un tramo de guía vacío "L" la diferencia de fase $\Phi o2 - \Phi o1$ es $\Delta\phi\mathbf{v} = -\beta\mathbf{v}.L$ y varía con la frecuencia.

- Ahora queremos construir un circuito de forma que su **ΔΦd** (variable con la frecuencia) sea tal que al compararlo con la guía vacía resulte en un diferencial:
  ΔΦd – ΔΦv = cte = **ΔΦ** deseada (tip. 45º, 90º, 180º)

Una forma evidente es ensanchar ò estrechar la guía puesto que la constante de propagación β varía con "a"

$$\Delta\Phi = [\beta v - \beta d].L = [2\pi/\lambda gv - 2\pi/\lambda gd].L$$

TE10 mode

$$\lambda c = c / Fc = 2.a$$

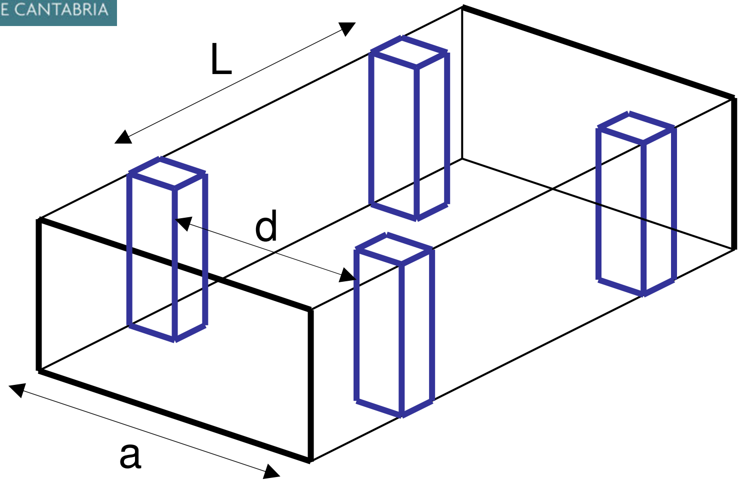
$$\lambda g = \frac{\lambda o}{[1 - (\lambda o/\lambda c)^2]^{0.5}}$$

$$\beta = 2\pi / \lambda g$$

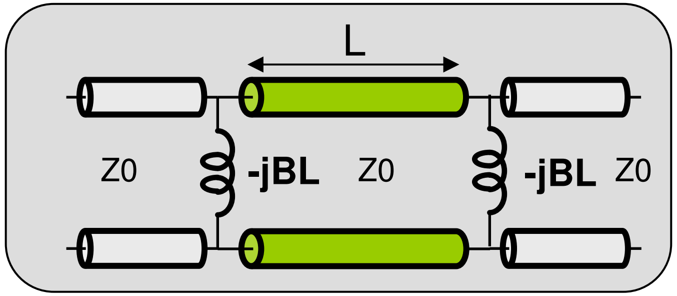
Detalles:

- Al reducir la guía cambiamos su Fc → el ancho de banda de trabajo se restringe.
- El salto entre guías afectará a la adaptación del desfasador
- El cambio de fase deseado se verificará en un **BW estrecho** ya que ΔΦ varía con la frecuencia.

Differential Phase-Shifter "Narrow Band"



Desfasador con doble discont.



Una forma alternativa consiste en introducir reactancias en la guía vacía. Si el diseño es correcto, las reflexiones debidas a estos elementos se cancelan mientras que sus efectos de fase son aditivos

Si llamamos **BLn** al valor normalizado de BL: BLn=BL.Zo entonces la matriz ABCD normalizada de la red es:

$$\begin{pmatrix} An & Bn \\ Cn & Dn \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -jBLn & 1 \end{pmatrix} \begin{pmatrix} \cos(\beta L) & j\sin(\beta L) \\ j\sin(\beta L) & \cos(\beta L) \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -jBLn & 1 \end{pmatrix}$$

Si la impedancia de entrada norm. Zin_n=(An+Bn)/(Cn+Dn) debe ser unidad para que exista adaptación, y ya que An=Dn entonces necesitamos Cn=Bn por lo que:

$$\beta.L = \pi/2 + \arctan(\mathbf{BLn}/2)$$

Por otro lado, el cambio de fase diferencial es:

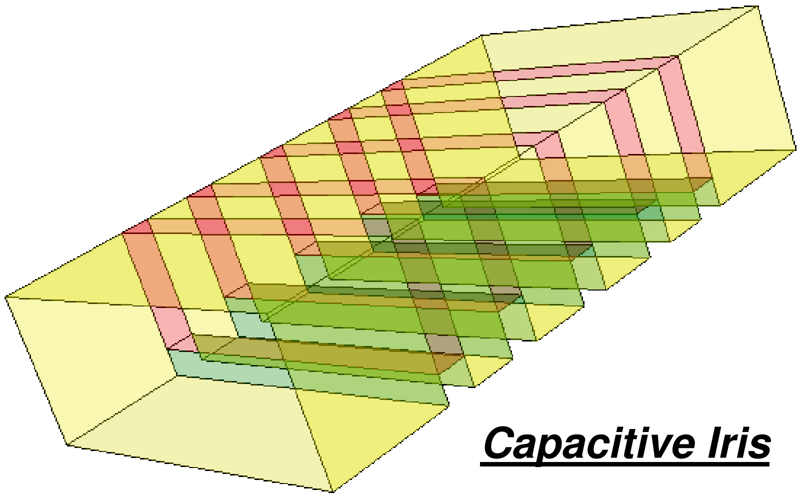
$$\Delta\Phi = \beta.L - [\pi/2 - \arctan(\mathbf{BLn}/2)]$$

$$\Delta\Phi = 2.\text{artan}(\mathbf{BLn}/2)$$

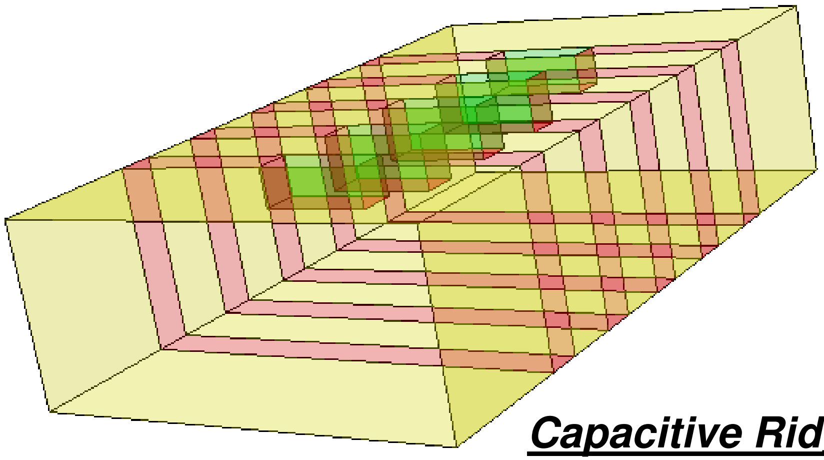
- Al contrario ocurre si introducimos reactancias capacitivas.
- Circuito de ***banda estrecha*** y sensitivo con la frecuencia

Differential Phase-Shifter “Broadband”

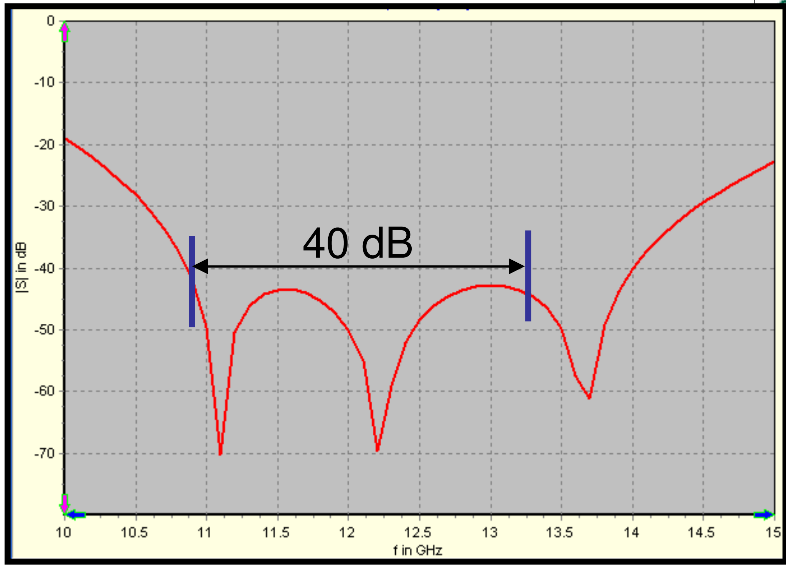
Low-Pass type

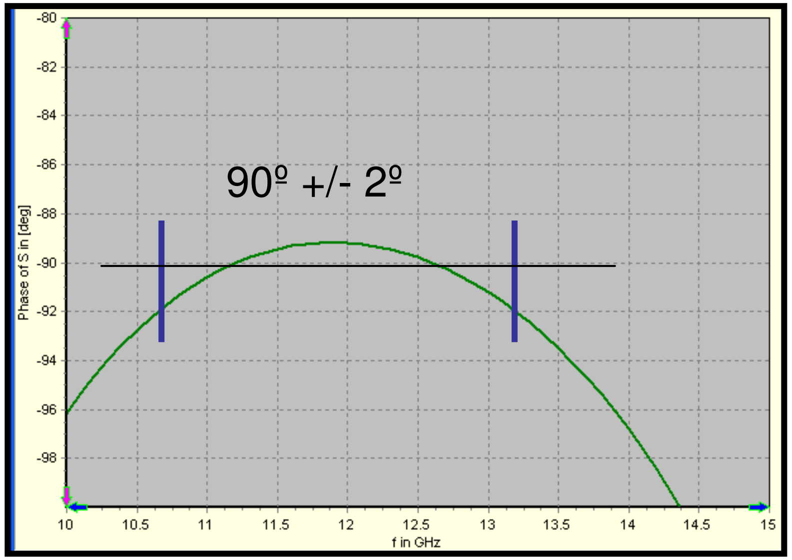


Capacitive Iris

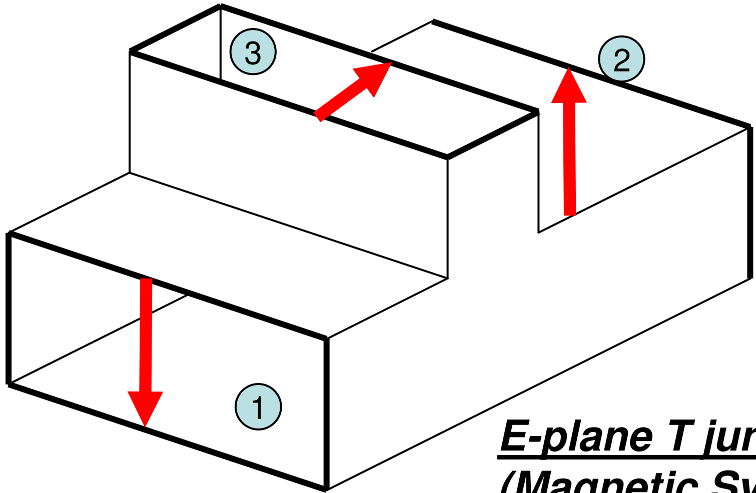


Capacitive Ridge

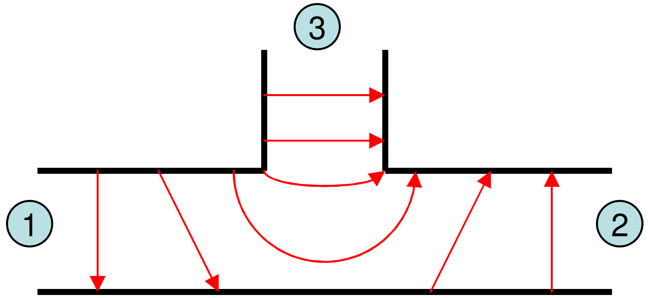




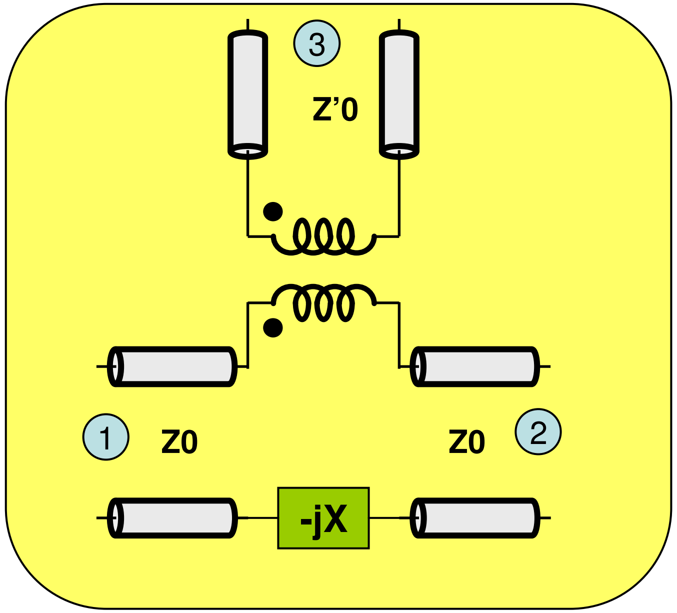
Waveguide Junctions



E-plane T junction
(Magnetic Symmetry)



Port 3 **Splits the input signal in 180º**

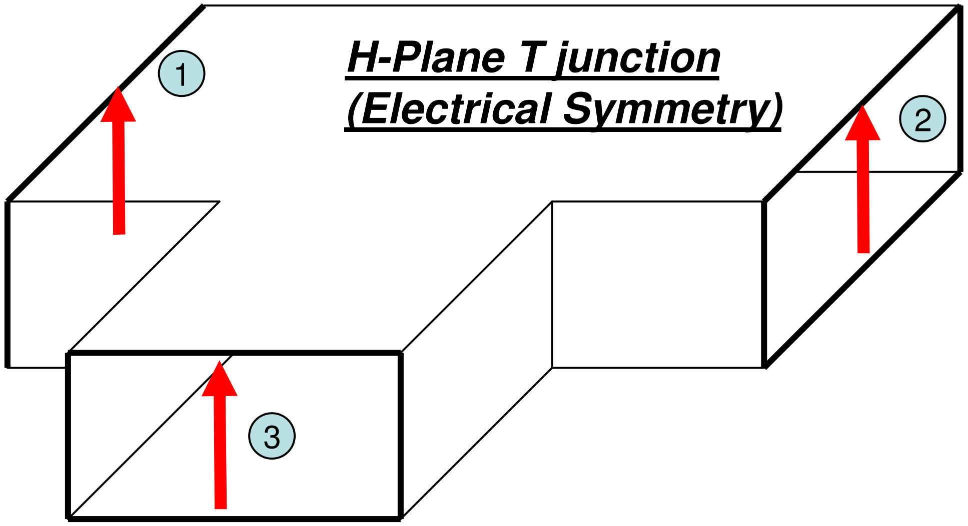


Equivalent Circuit: **Series connection**

- The THREE ports cannot be matched simultaneously.

- Port 3 splits power in **phase opposition 180º**, but power splitting is not 3db due to mismatching.

- If port 3 is matched, power splitting is 3dB but S11 and S22 will have 6dB return loss.

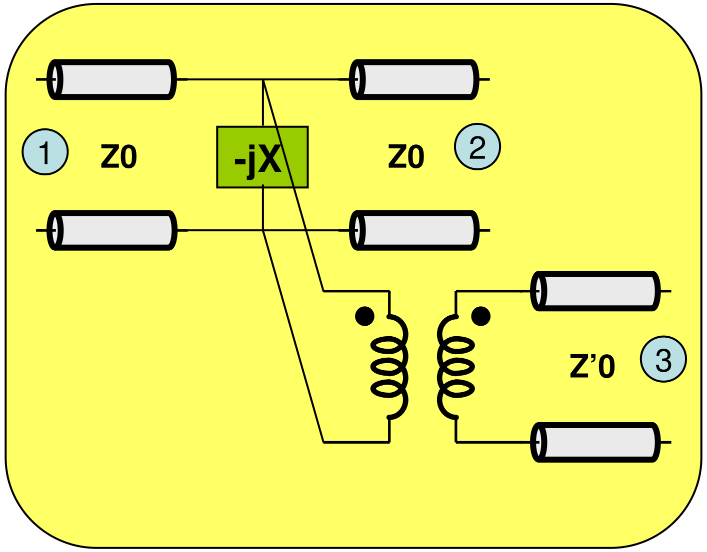


Port 3 **Splits the input signal in 0º**

- The THREE ports cannot be matched simultaneously.

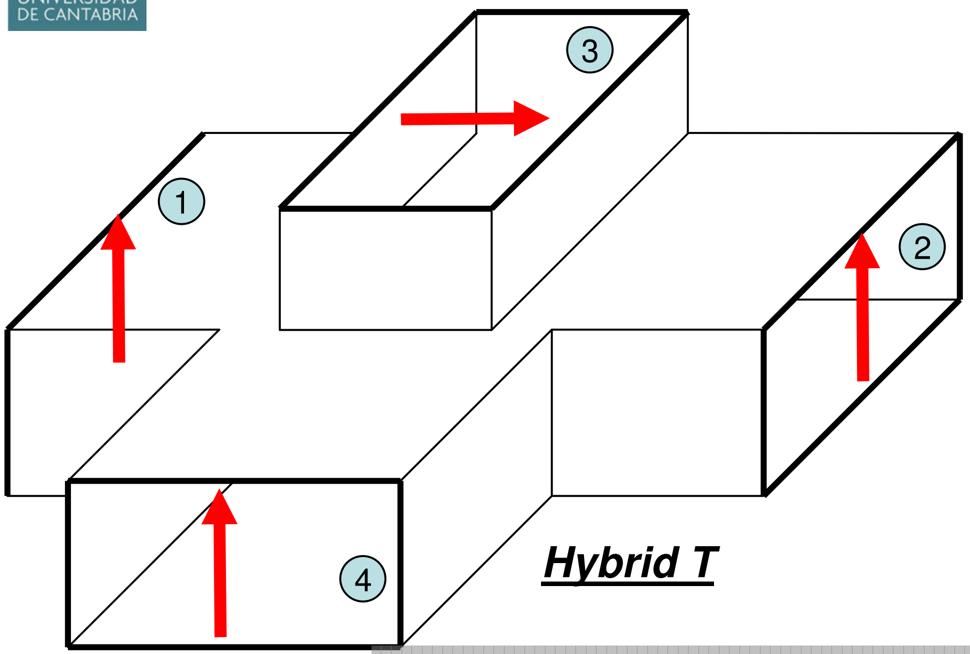
- Port 3 splits power in **phase 0º**, but power splitting is not 3db due to mismatching.

- If port 3 is matched, power splitting is 3dB but S11 and S22 will have 6dB return loss.



Equivalent Circuit: **Parallel connection**

Hybrid Waveguide Junctions – Magic Tee

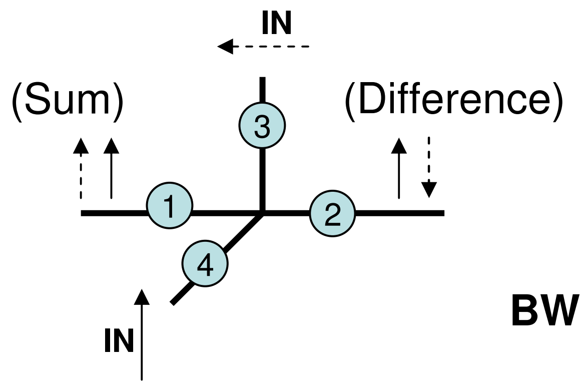


- Ports 1 and 2 decoupled
- Ports 3 and 4 decoupled
- Power splitting in 0º and 180º

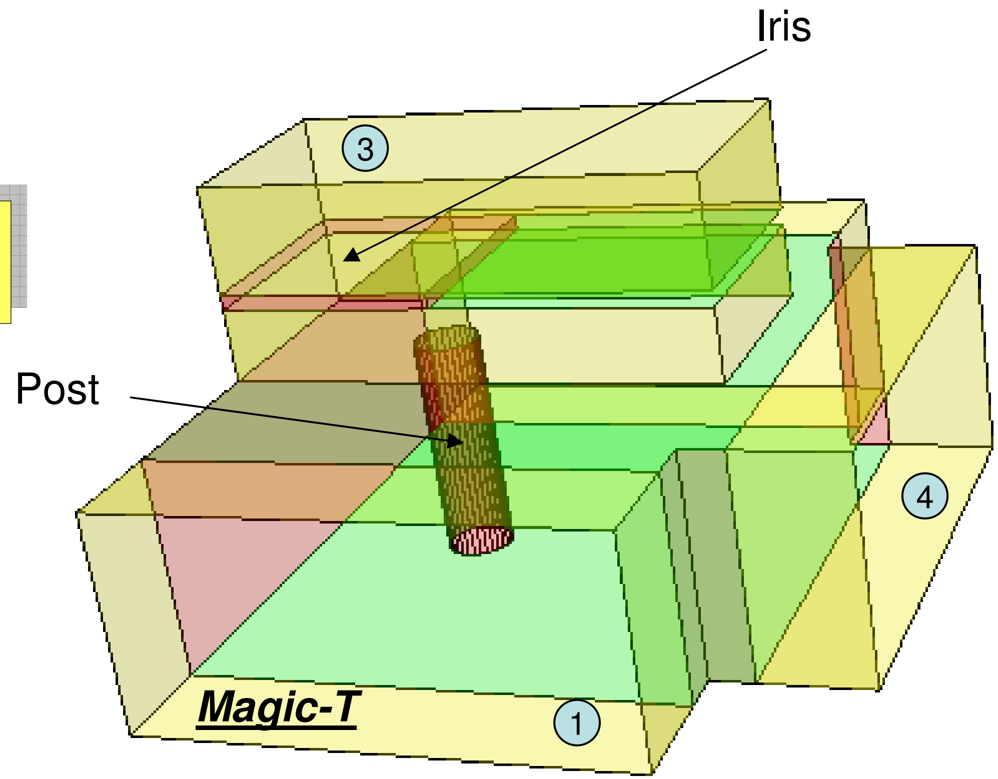
<u>Magic-T</u>.- Completely matched Hybrid T.
It is necessary to introduce some discontinuities
In the junction.
- In this case, power splitting is always **3dB**.

Useful as Power Divider or Power Combiner 0º ò 180º

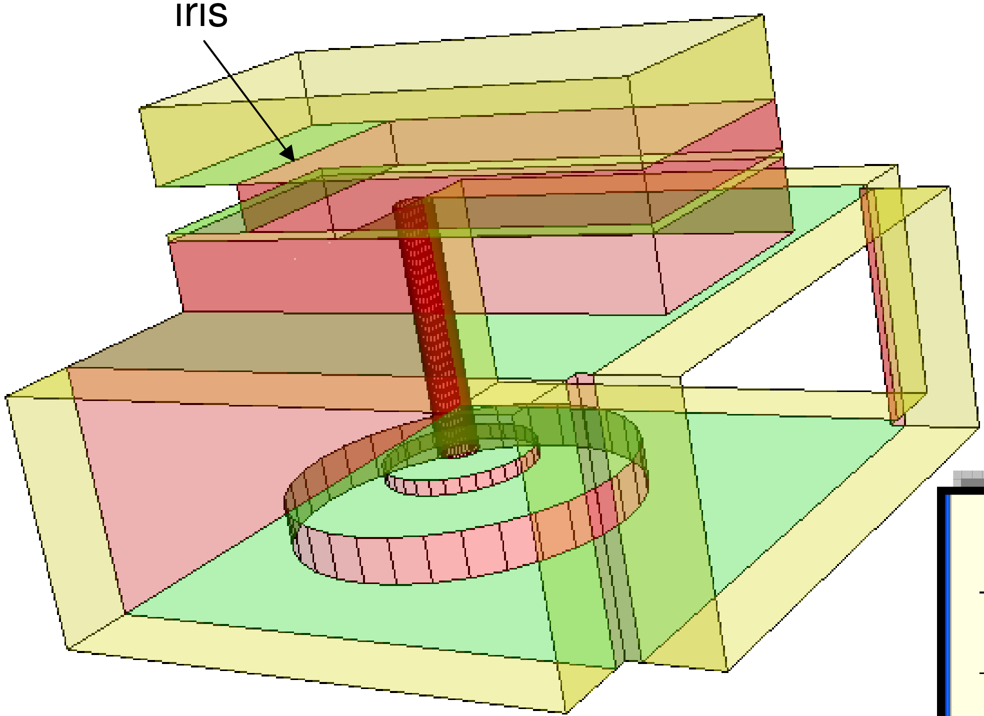
<u>Example:</u>



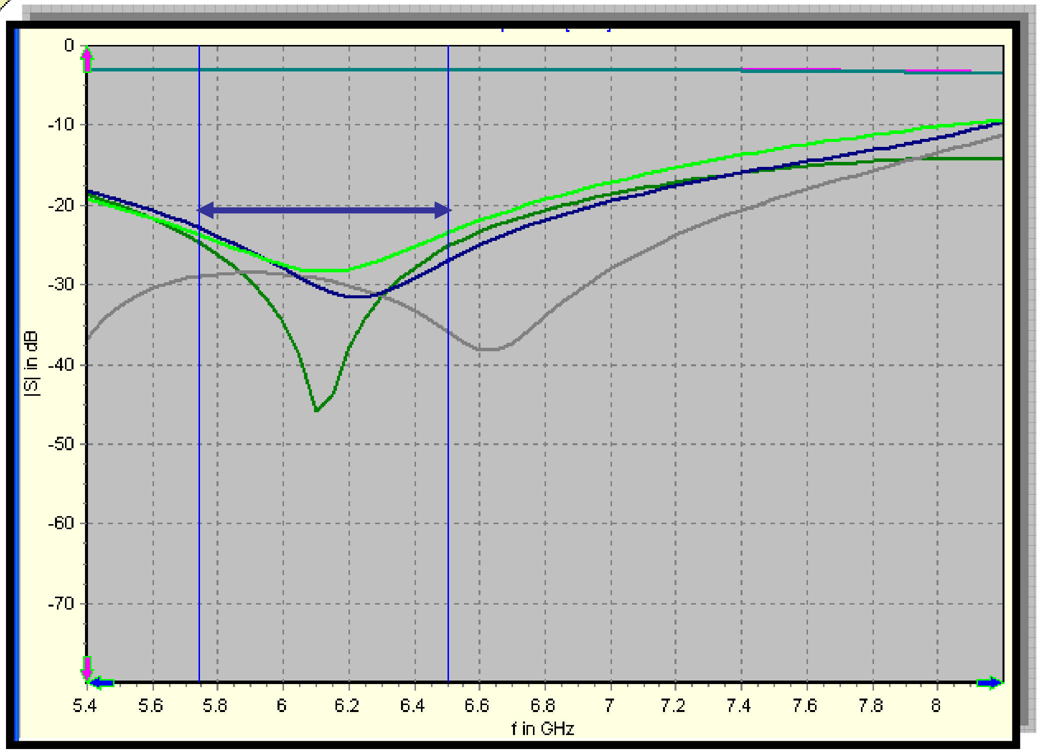
BW: 10-20%



Hybrid Waveguide Junctions – Magic Tee



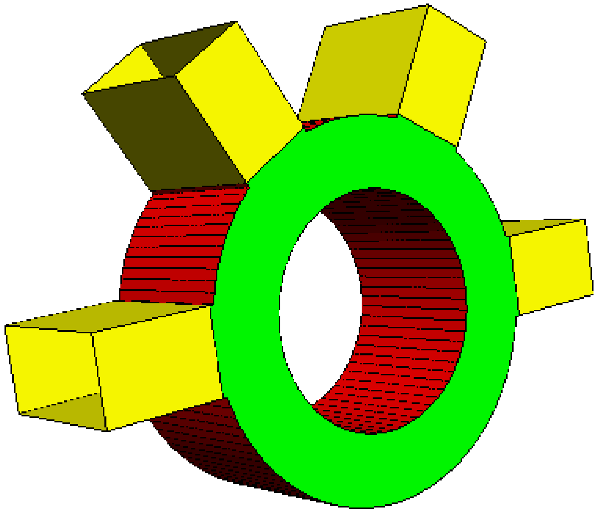
Useful as Power Divider or Power Combiner 0º ò 180º

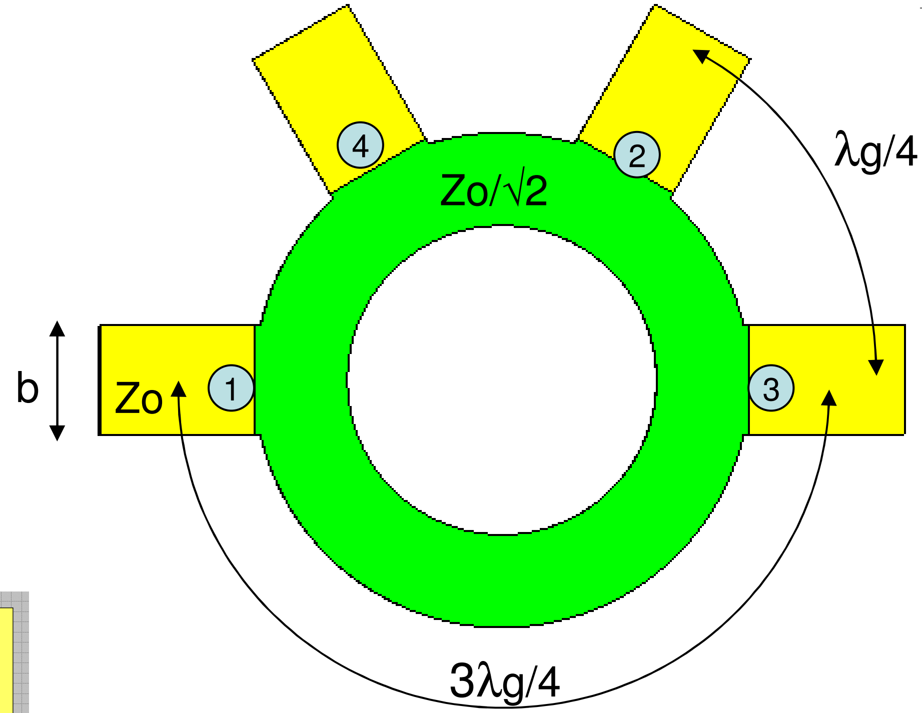


Optimized Magic-T

BW : 12%

Four-Port Waveguide junction (rat trace)



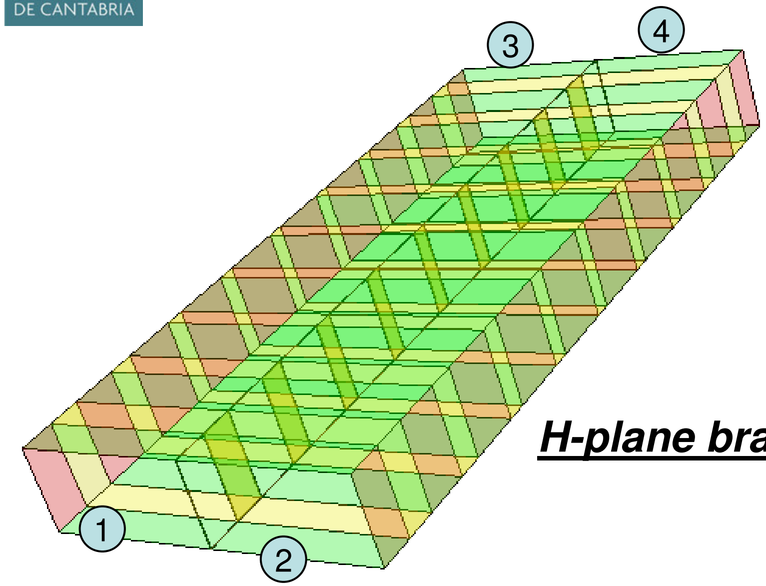


Useful as Power Divider
or Power Combiner 0º ò 180º

BW: 10%

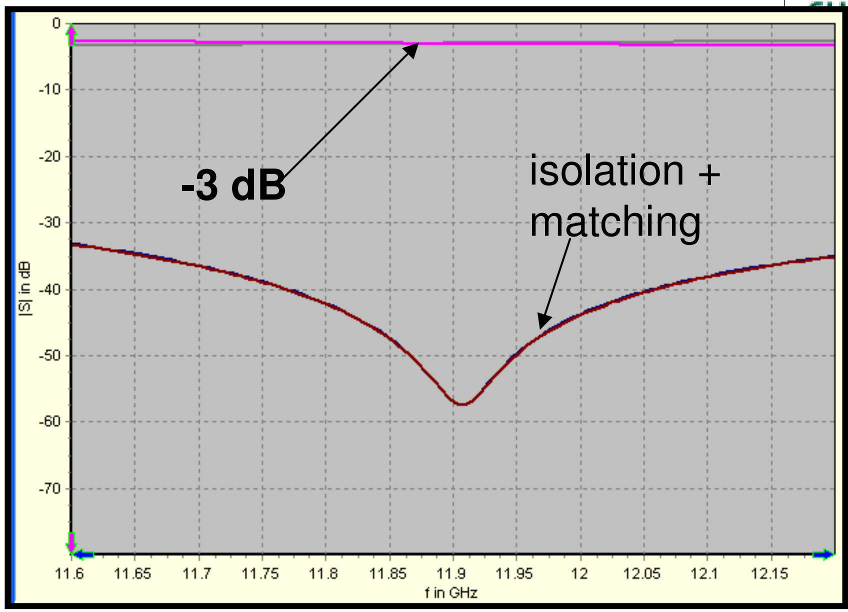
-Ports 1 and 2 decoupled
-Ports 3 and 4 decoupled
-(1) splits toward (3) and (4) in phase opposition (3dB).
-(4) splits toward (1) and (2) in phase (3dB).

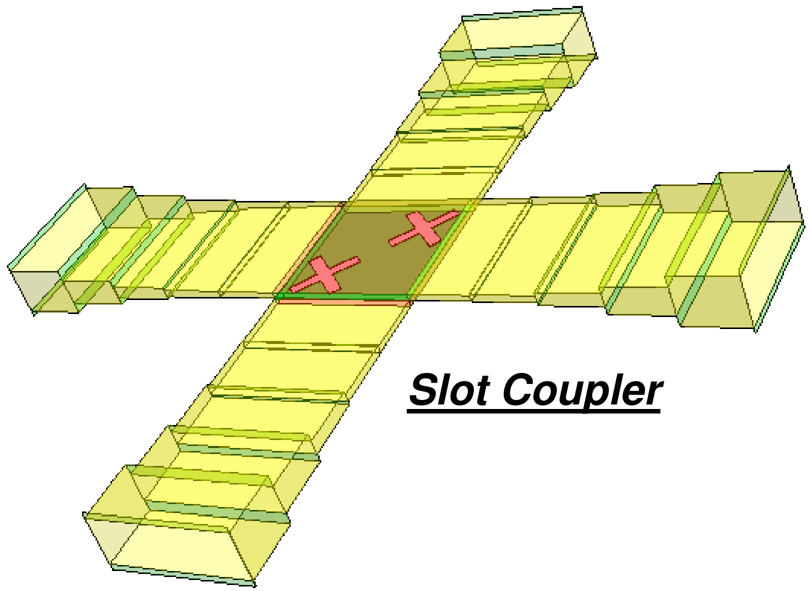
} Path differences



H-plane branch coupler

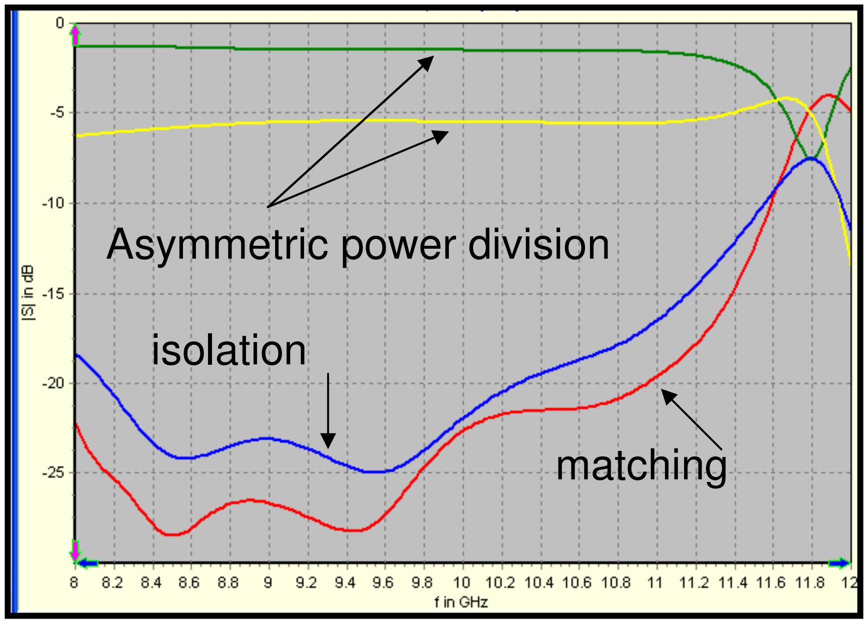
BW: 10%



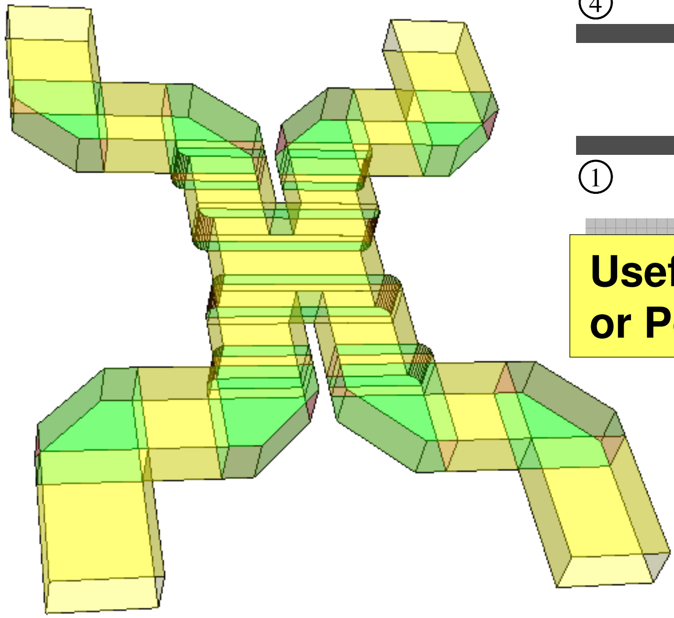


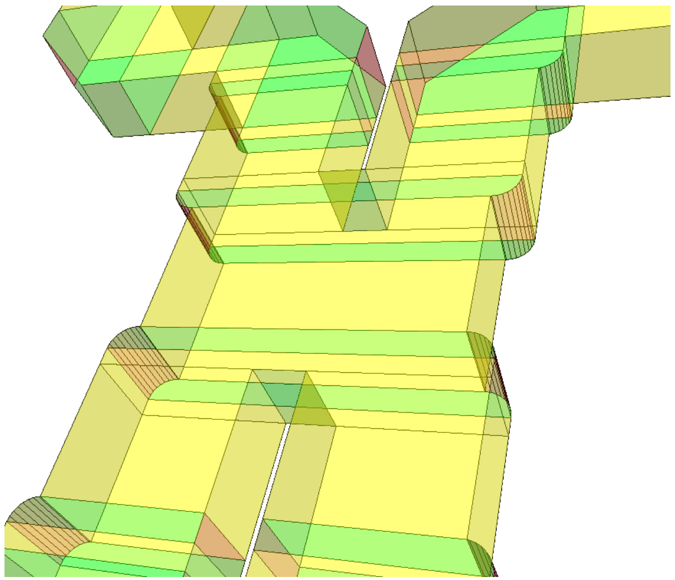
Slot Coupler

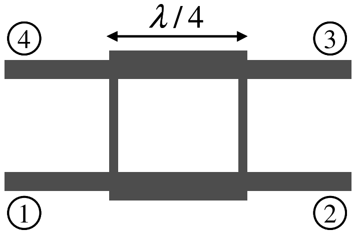
BW: 20%



3dB – 90º Couplers







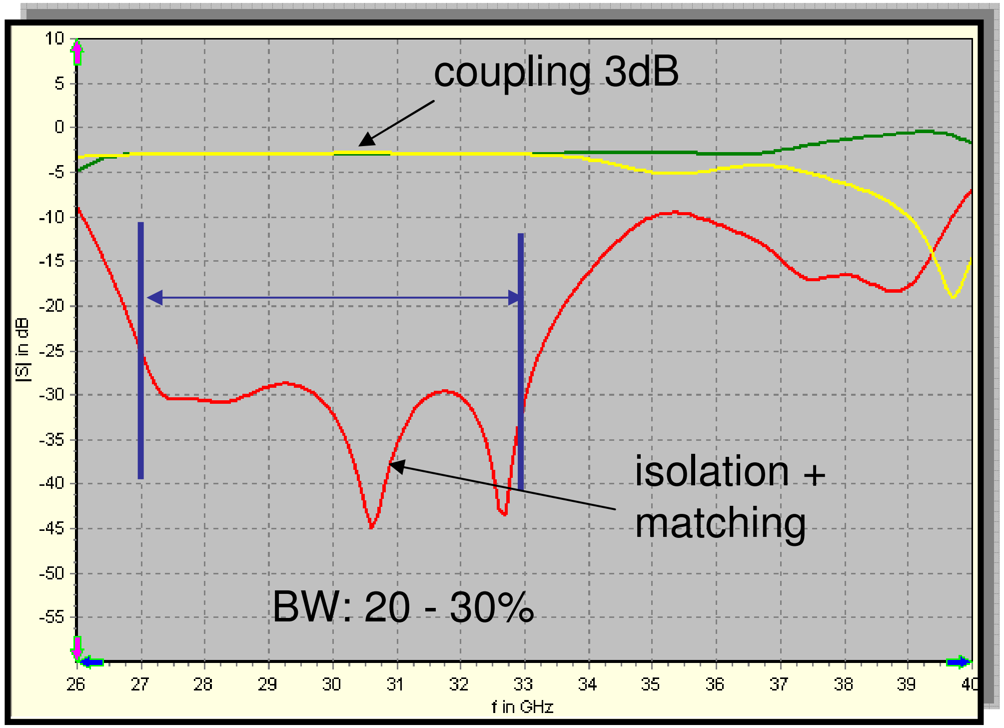
Homonym in microstrip

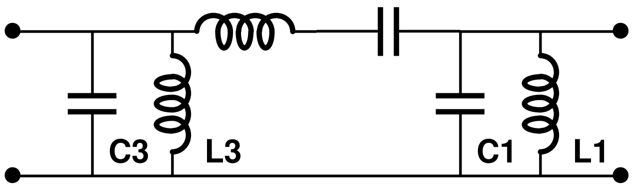
Useful as Power Divider or Power Combiner 90º

3dB Ribblet coupler

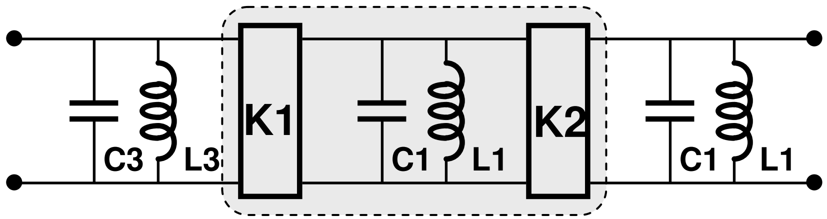
Phase shift : 90º

BW: 20%

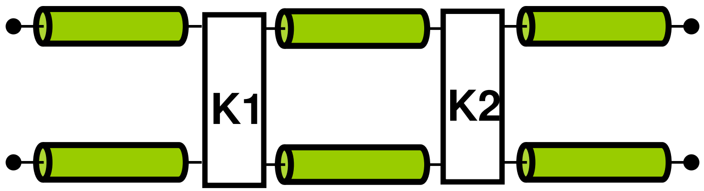




Discrete Pass-Band circuit

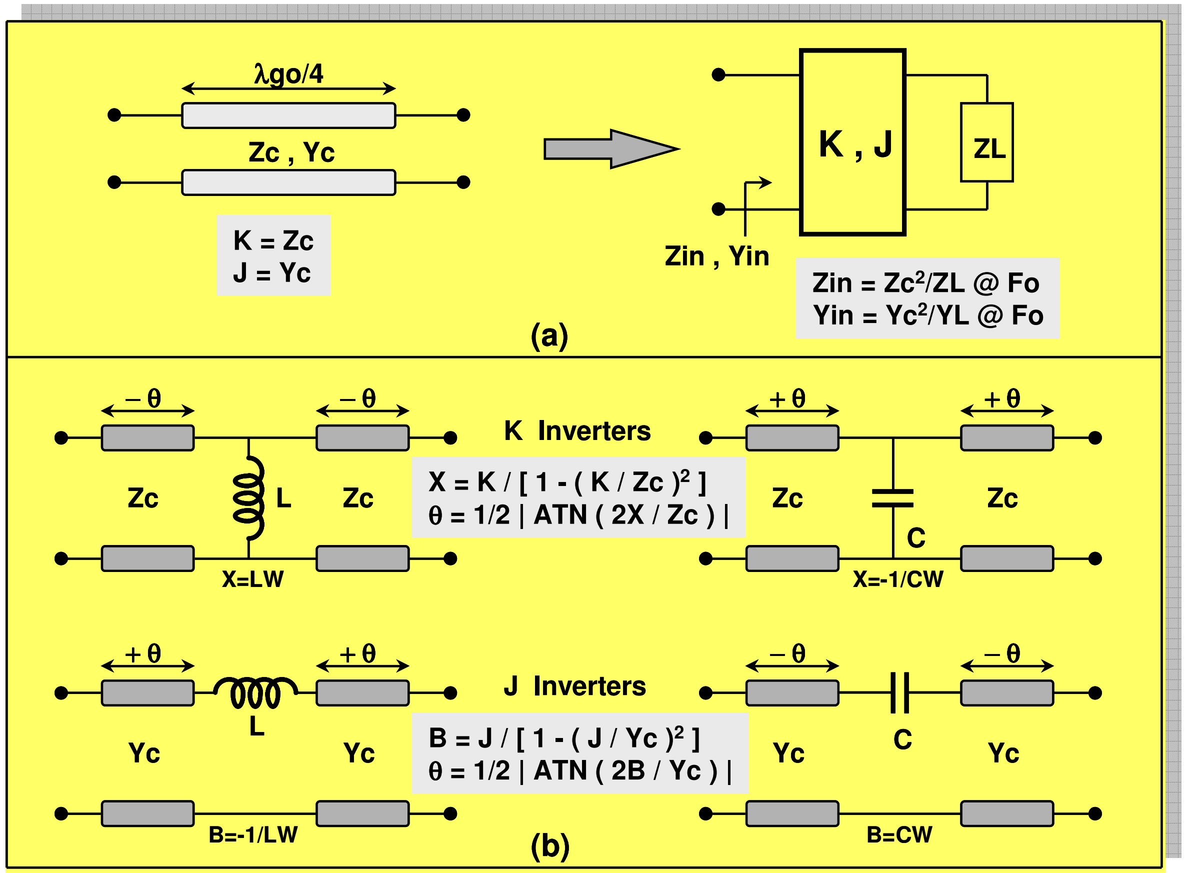


Using Inverters

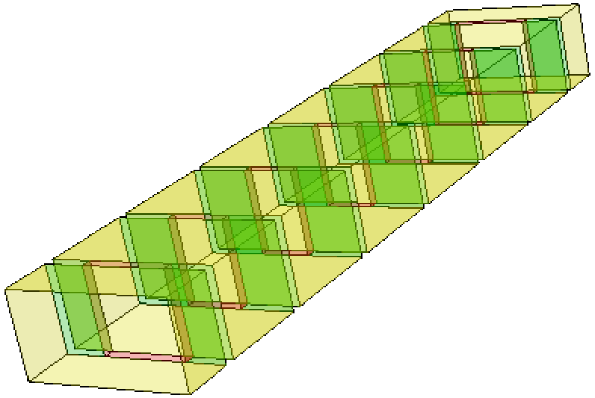


Inverters + waveguide sections

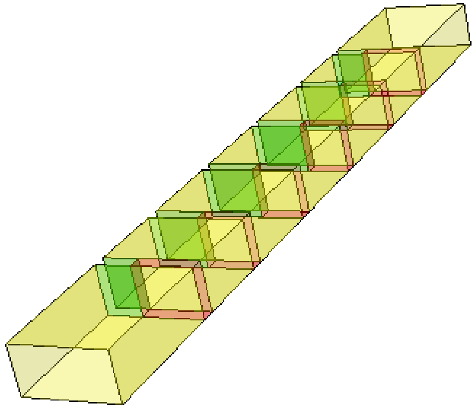
Some examples for Inverters



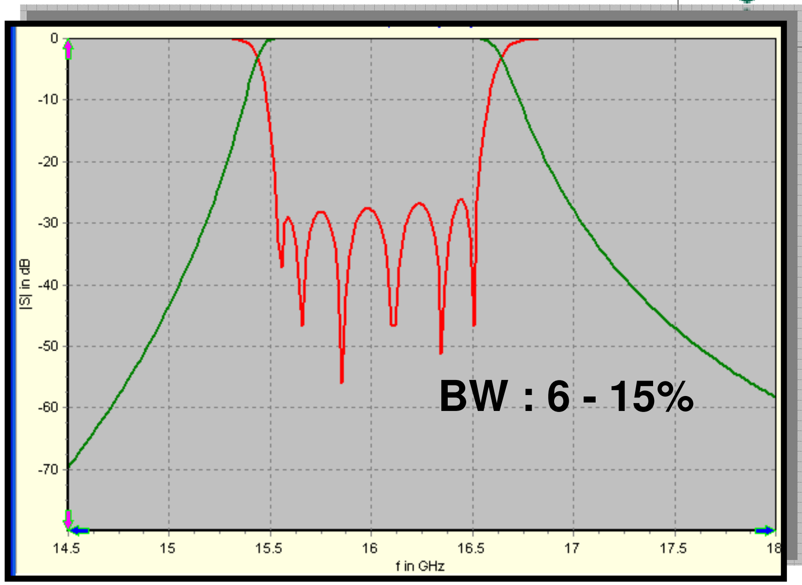
Band-Pass Waveguide Filters

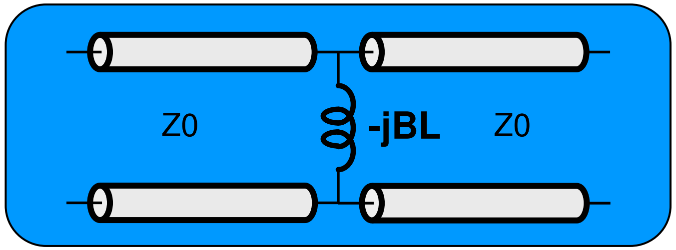


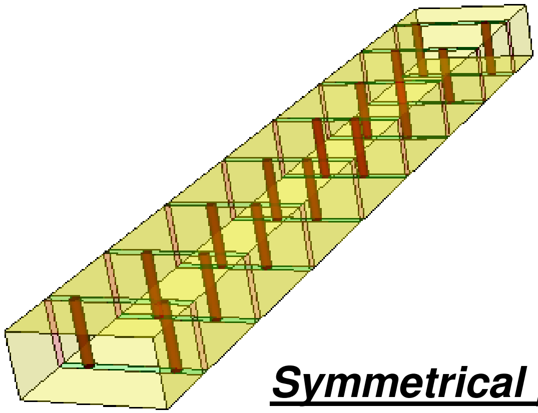
Symmetrical Iris



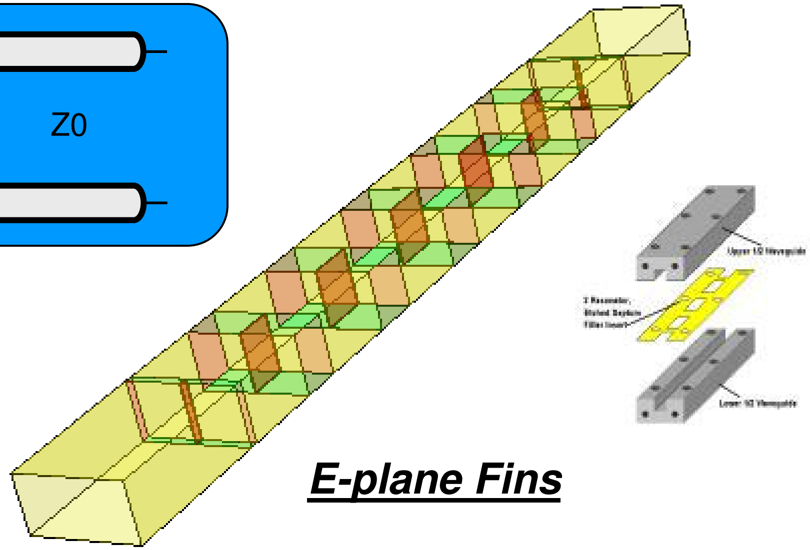
Asymmetrical Iris





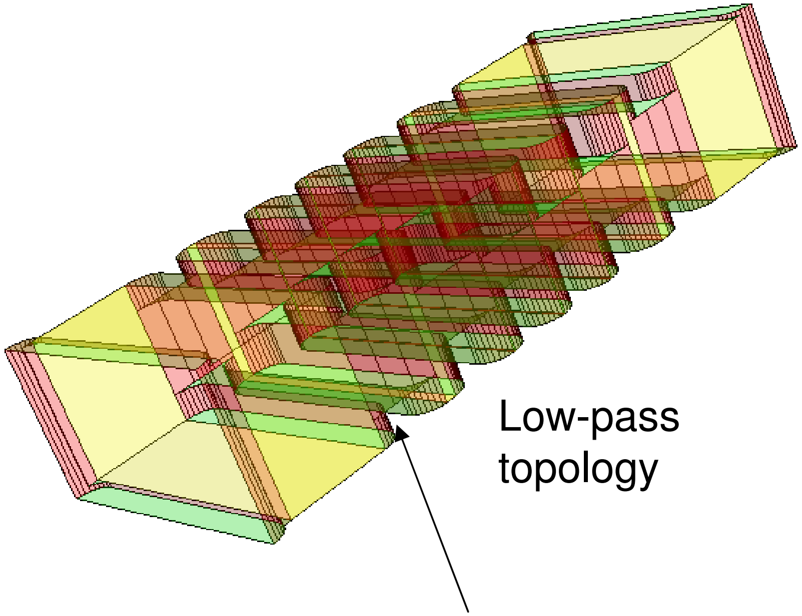


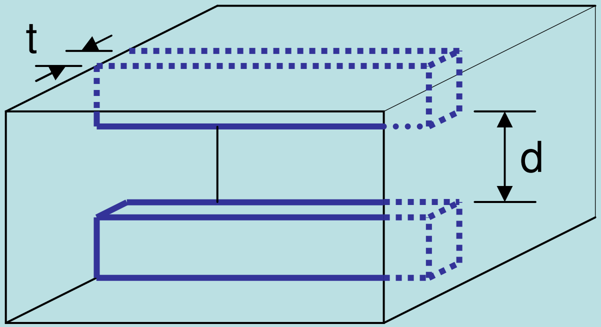
Symmetrical pairs of Posts



E-plane Fins

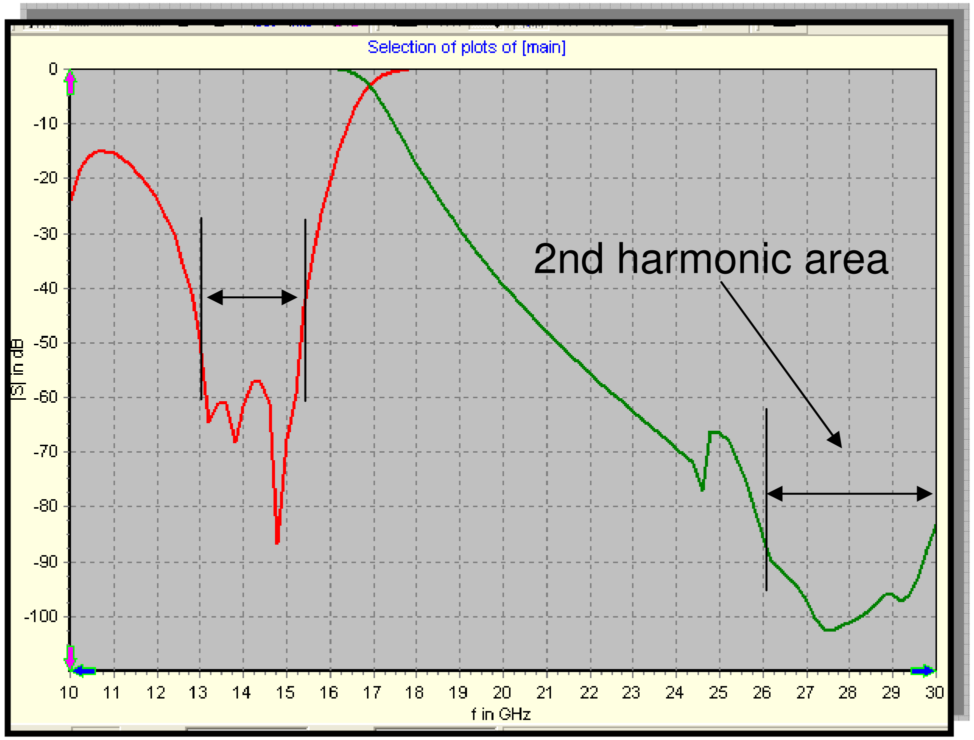
Low-Pass Waveguide Filters





Symmetrical E-plane Iris

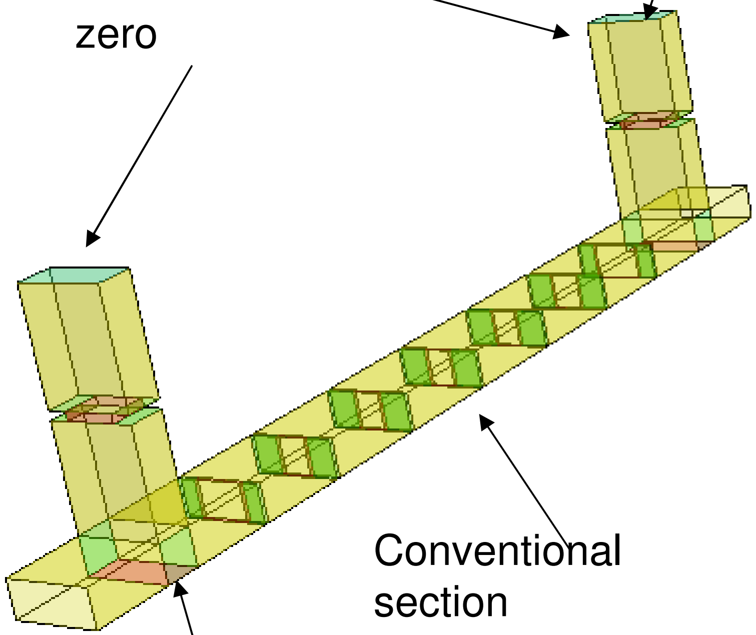
Destroys 2nd Harmonic in Microwave transmitters



Elliptic Waveguide Filters

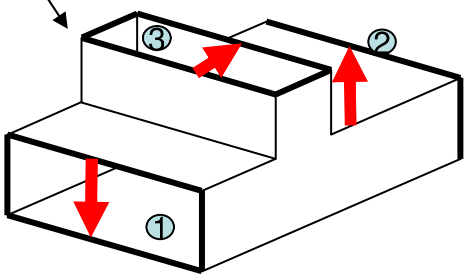
Transmission zero

Short circuit

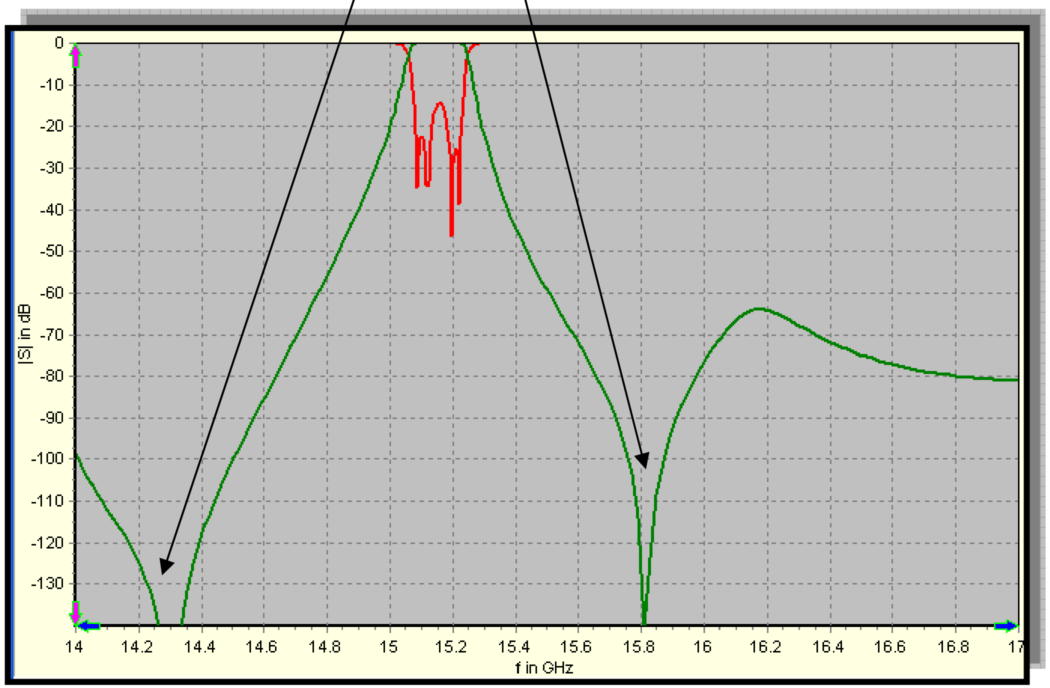


Conventional section

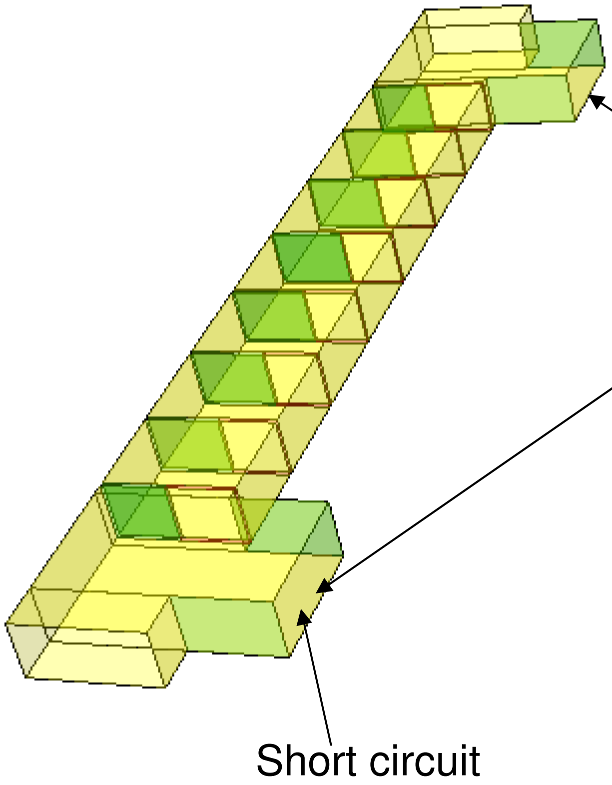
E-plane Tee + Series Stub

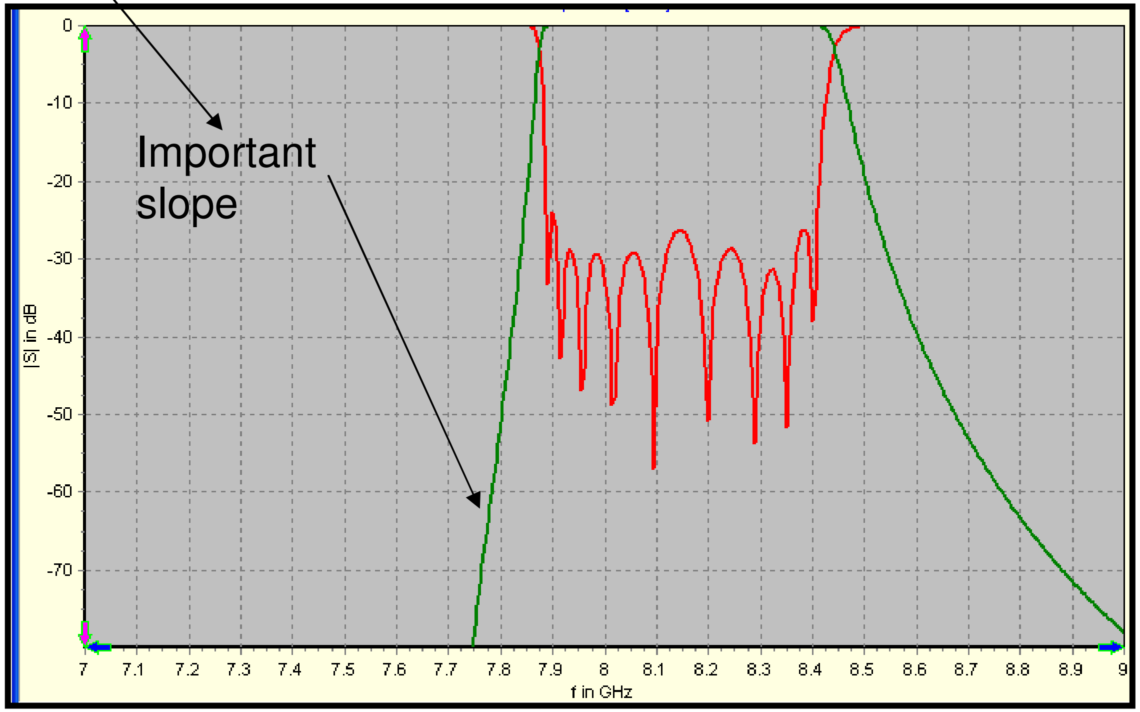


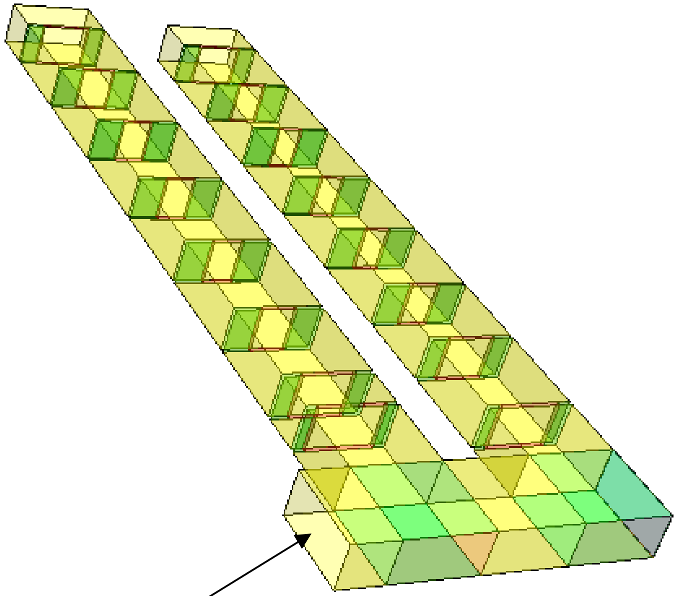
Transmission Zero



Supplementary Rejection at one side of the filter

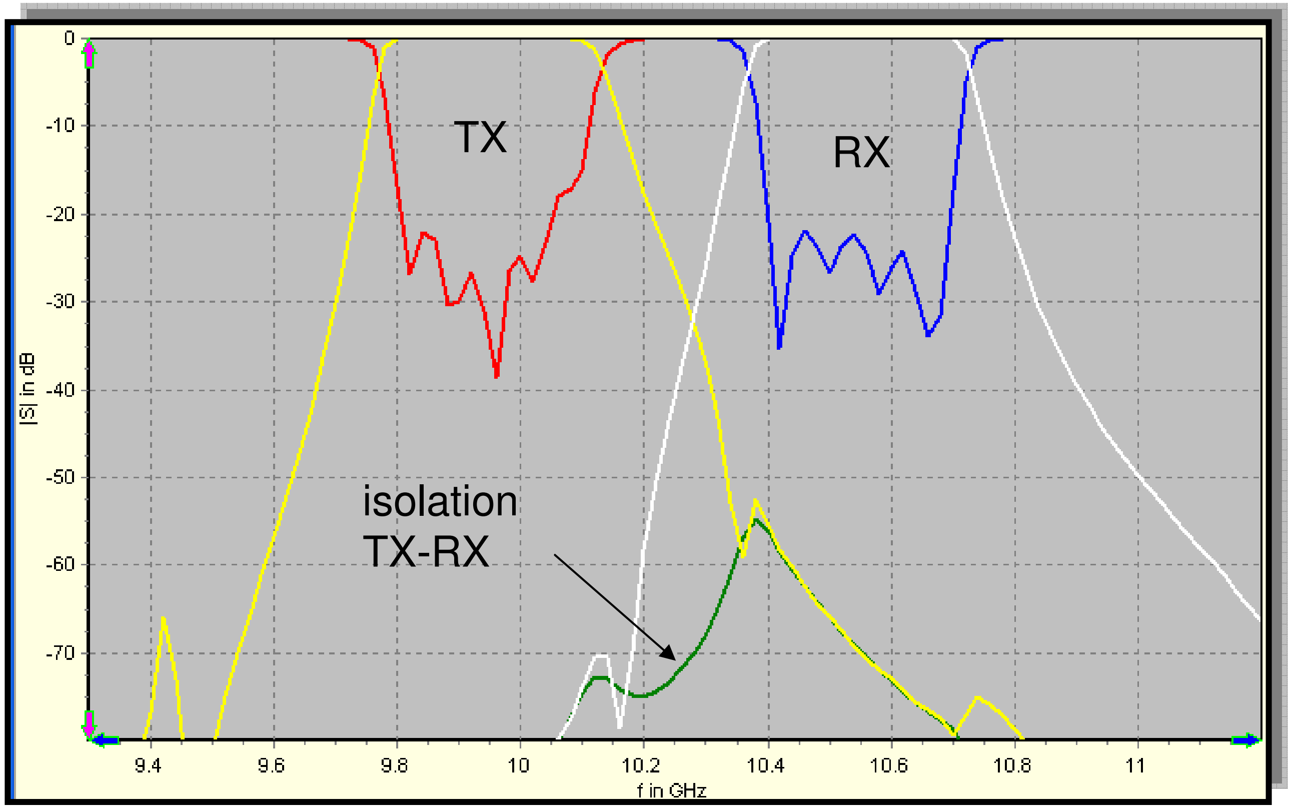




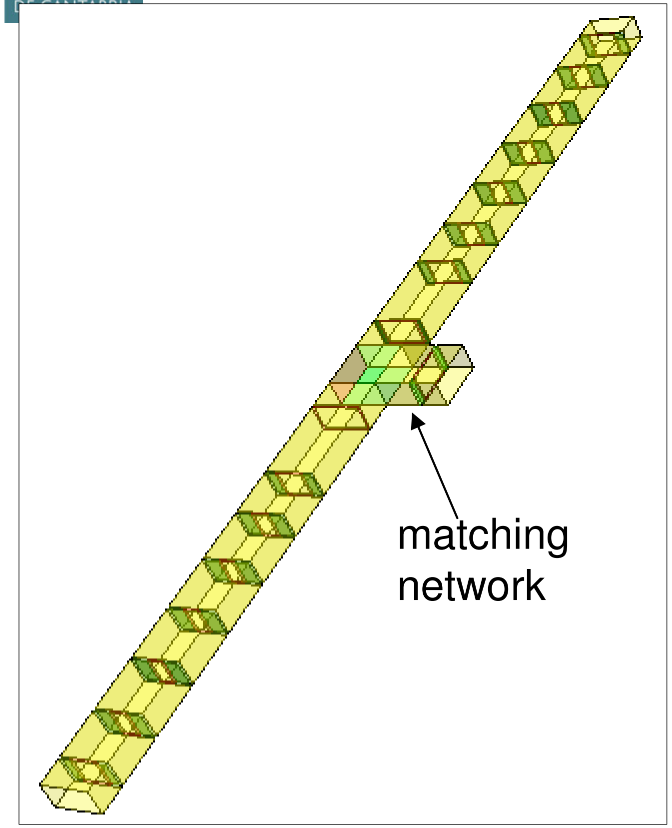


Common Port
Towards the antenna

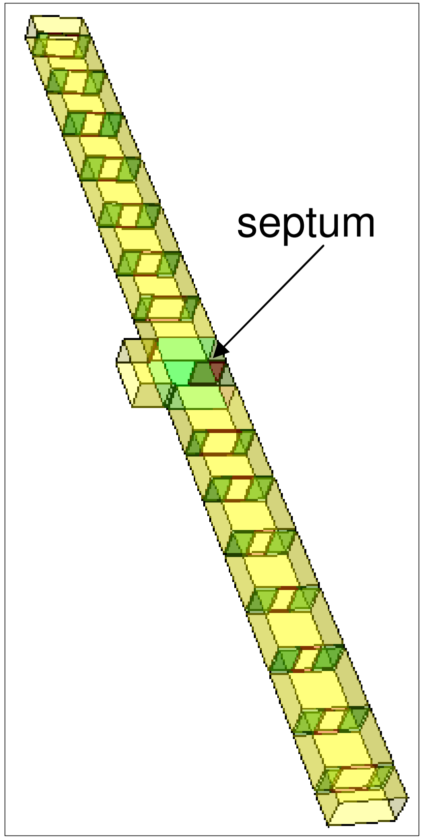
To select two different frequency bands
(in theory completely isolated)



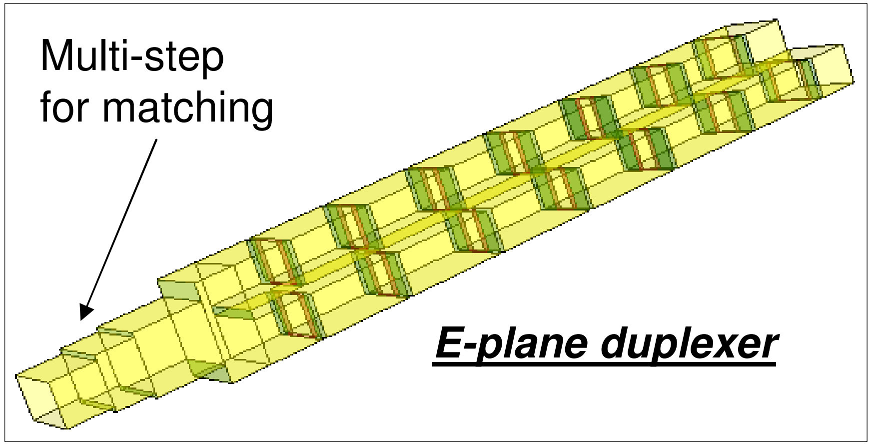
DUPLEXERS (variants)



H-plane duplexer (matched T)

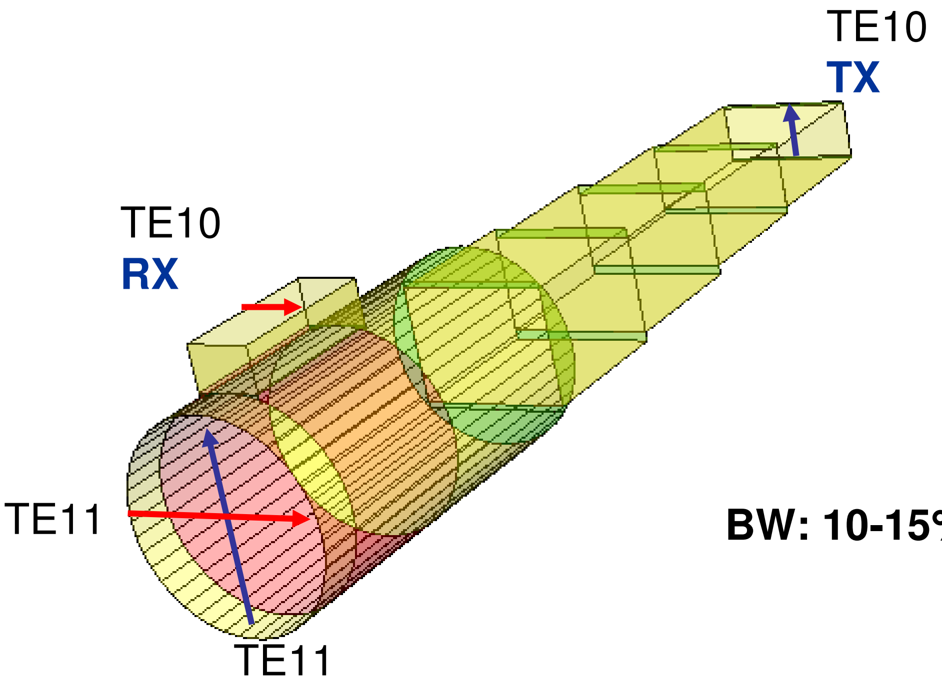


H-plane duplexer (septum)



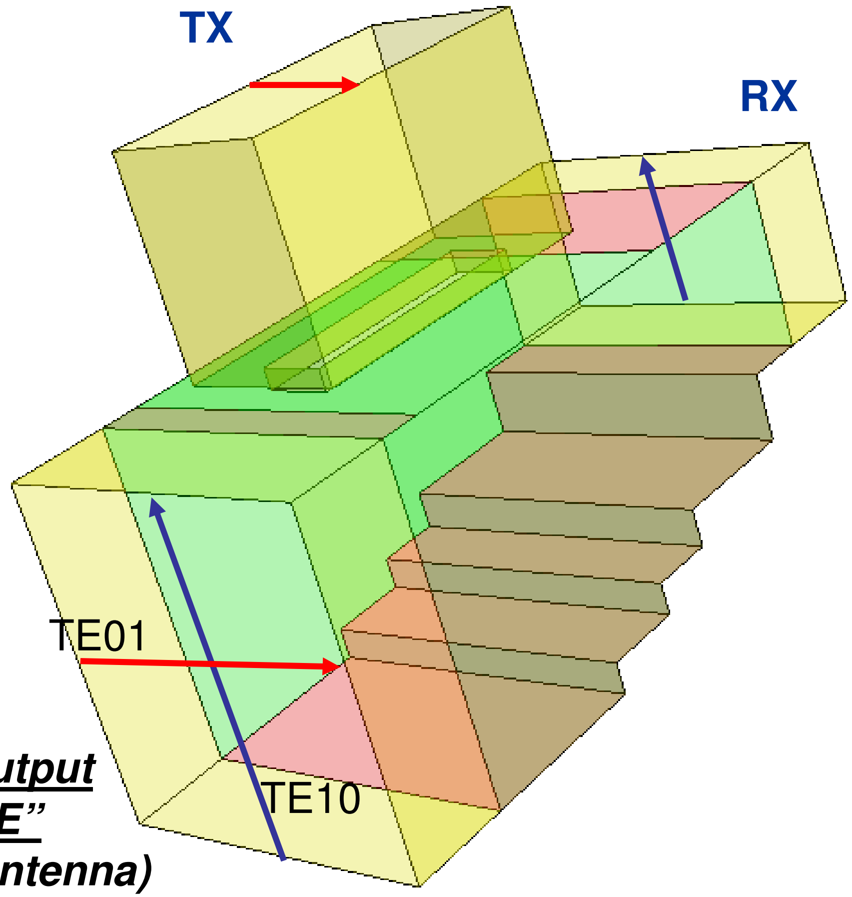
ORTHOMODE JUNCTIONS (OMT)

- In the common waveguide TX and RX are orthogonal: infinite isolation.
- Operation in the same band or in different frequency bands



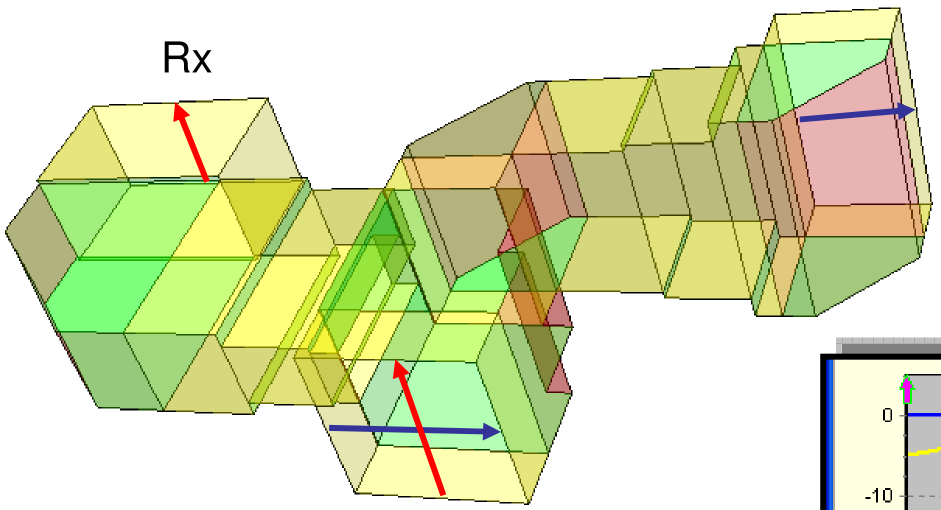
Common output
"CIRCULAR"
(towards the antenna)

BW: 10-15%



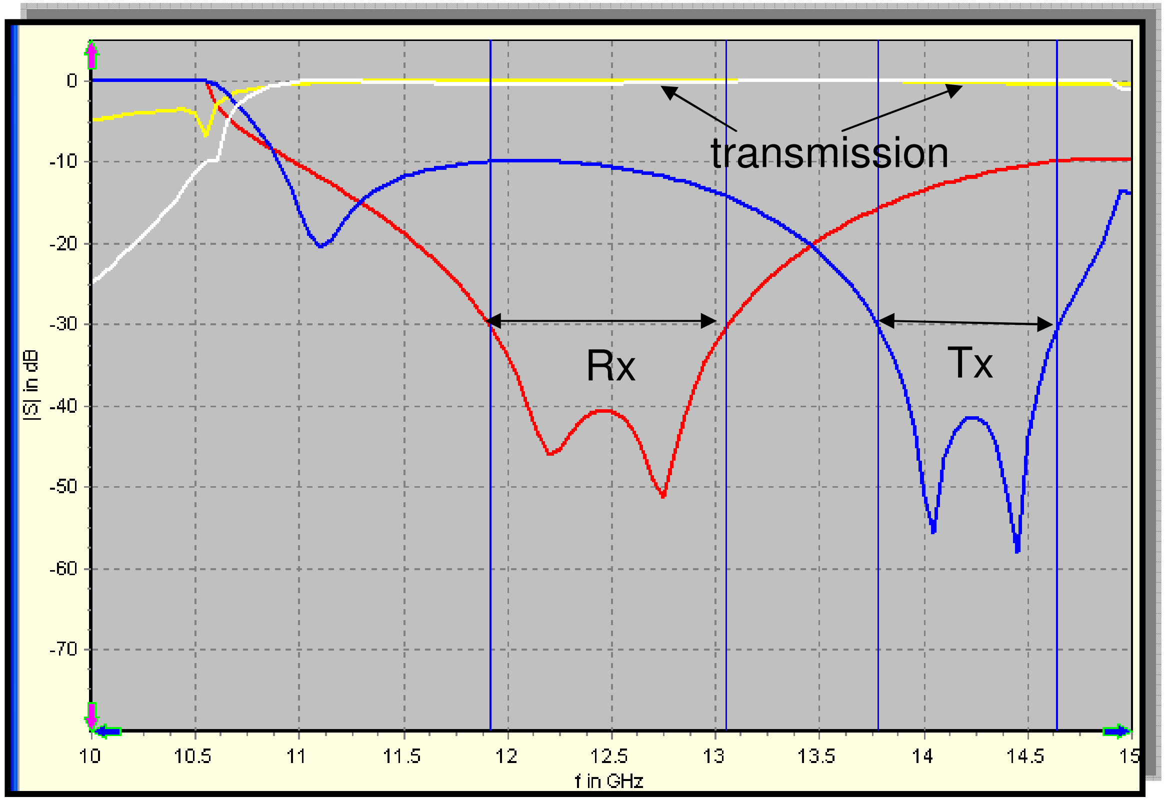
Common output
"SQUARE"
(towards the antenna)

DUAL-BAND ORTHOMODE

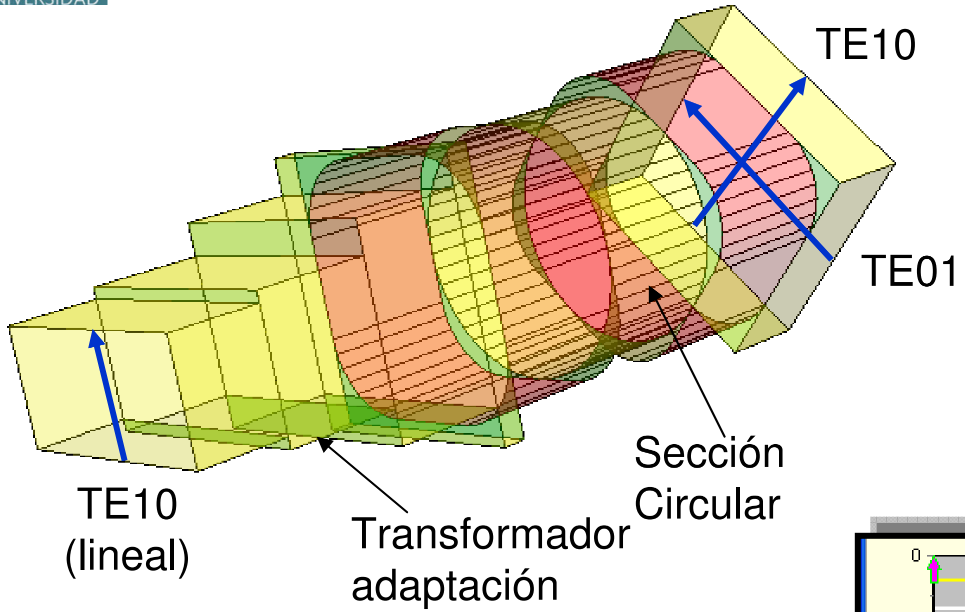


WR75: Ku band

Common output
"SQUARE"
(towards the antenna)



POLARIZERS for Circular Polarization



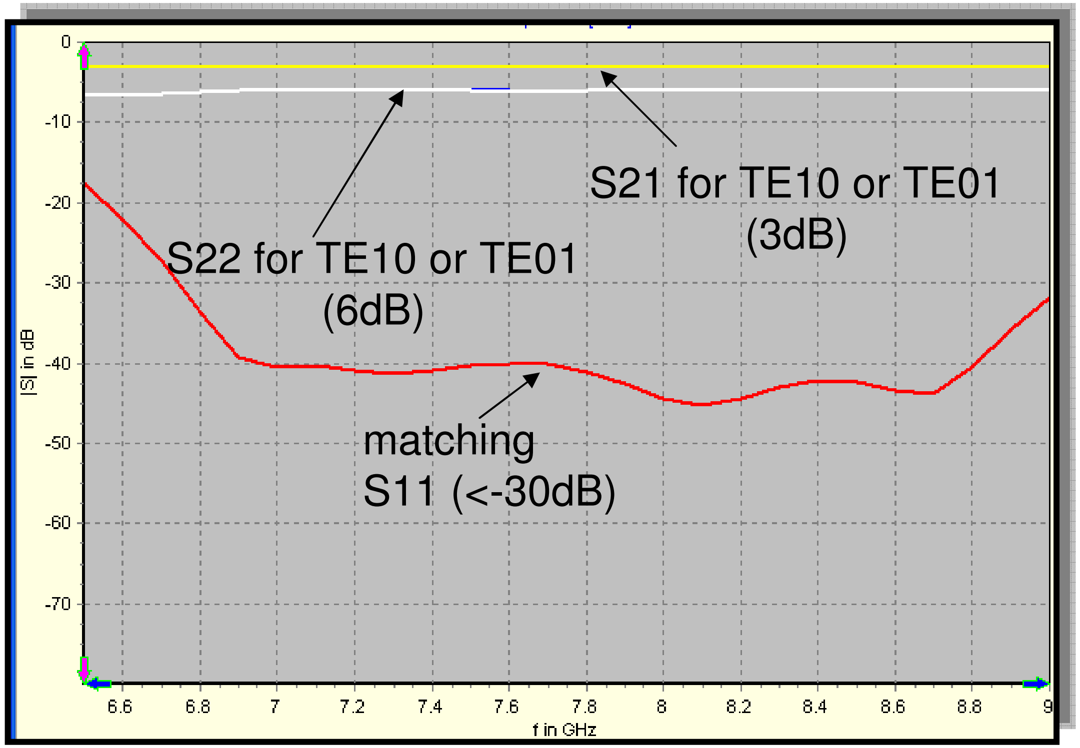
-To convert a LINEAR polarization to a CIRCULAR polarization:

1º.- Split the input signal TE10 into two orthogonal modes TE10 and TE01 through the use of a square waveguide rotated 45º

2º.- Delay one mode with respect to the other by 90º.

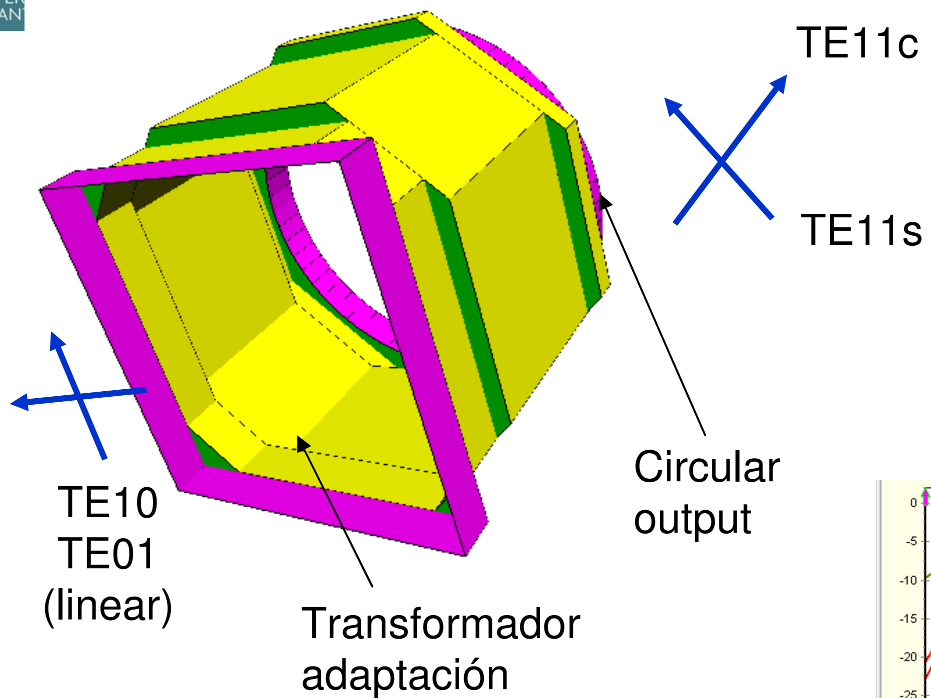
Phase shift between TE10 and TE01 is ZEROº

BW: 40%



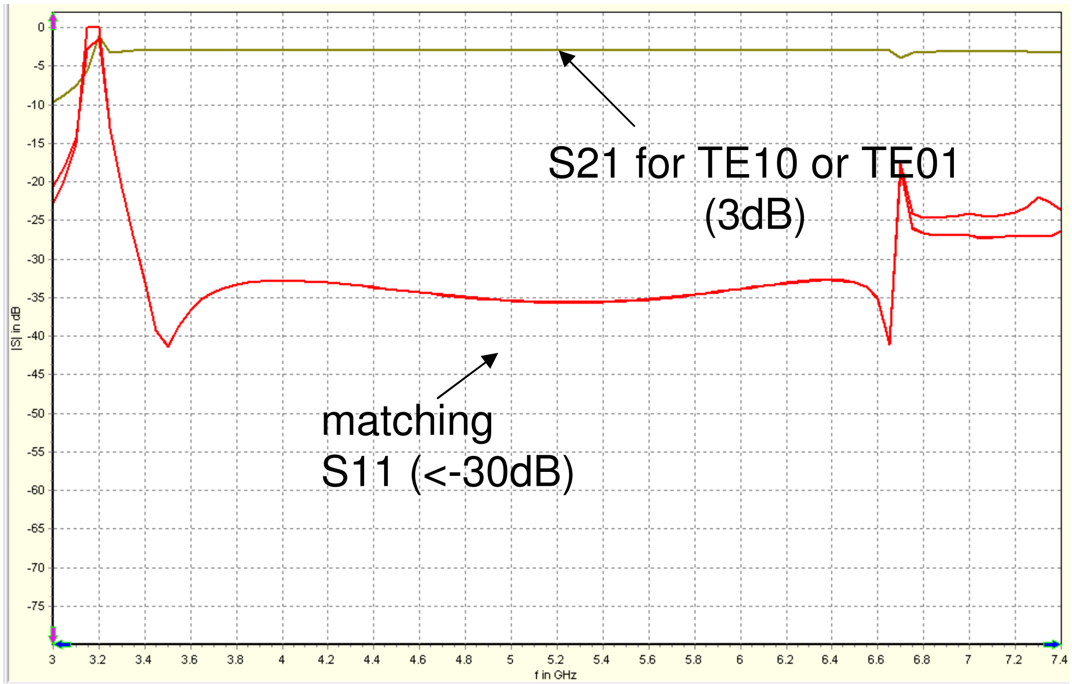
POLARIZERS for Circular Polarization

- Same idea but using octagonal sections



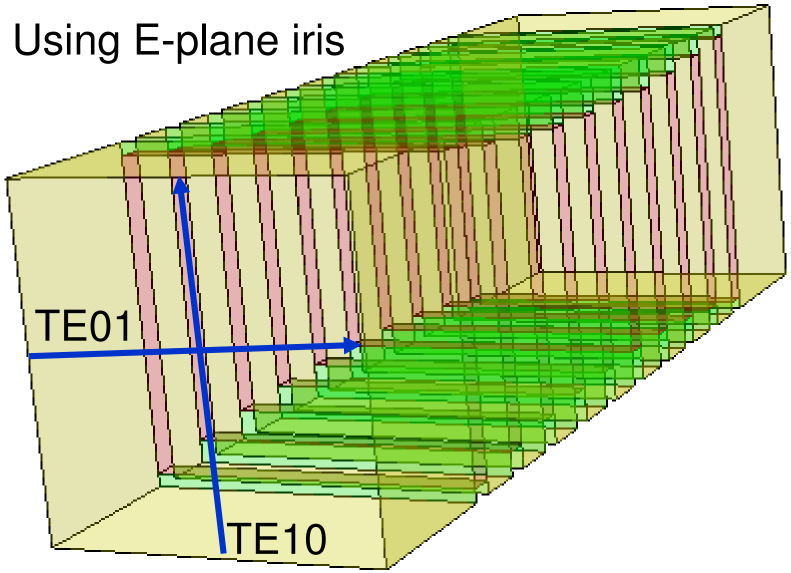
Phase shift between TE10 and TE01 is ZEROº

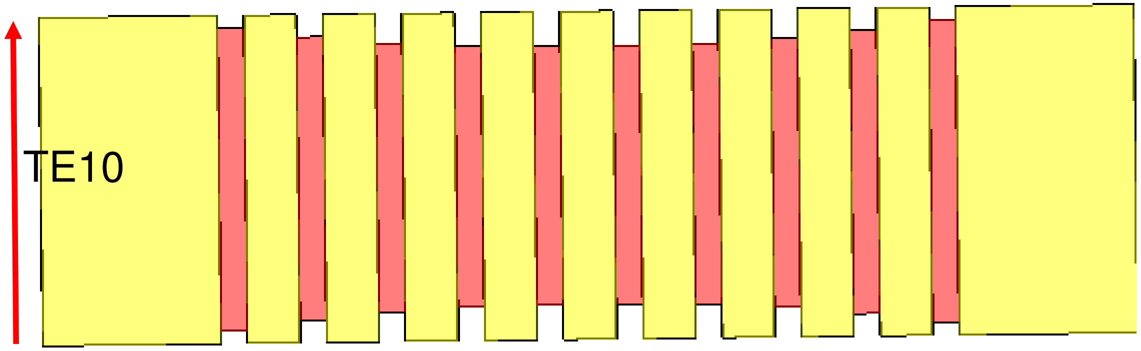
BW: 66%



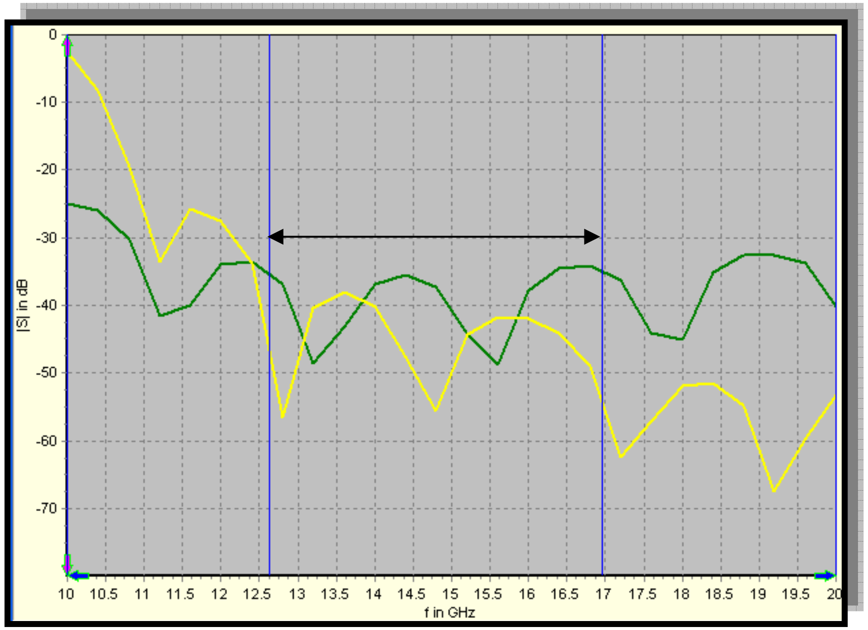
POLARIZERS for Circular Polarization

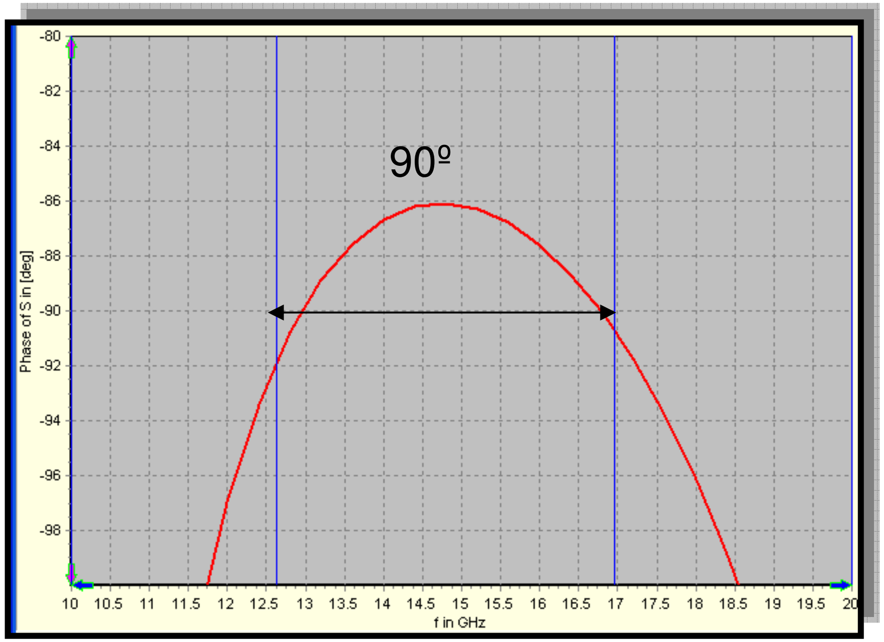
Using E-plane iris

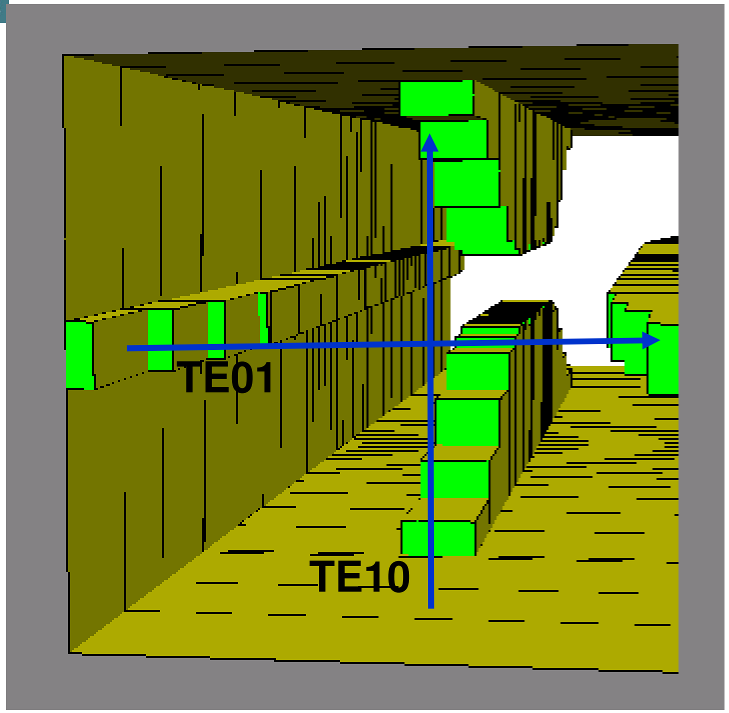




TE10 mode is delayed 90º with respect to TE01 mode

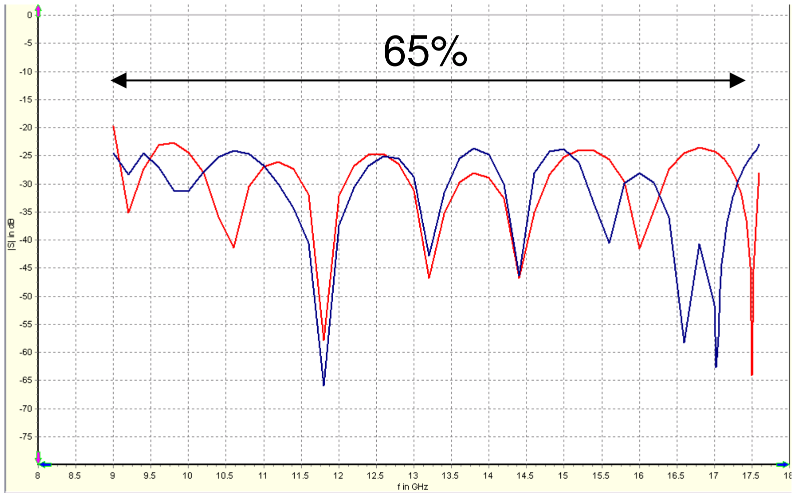


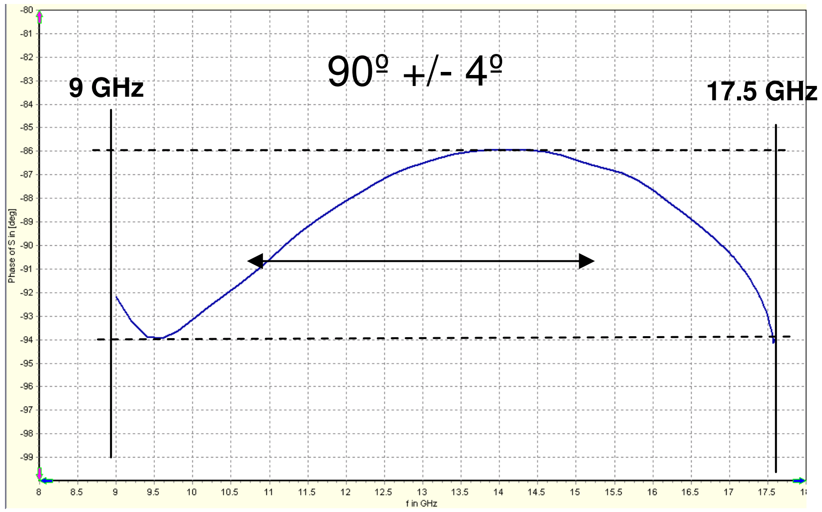




Using Ridge waveguide

TE10 mode is delayed 90º with respect to TE01 mode

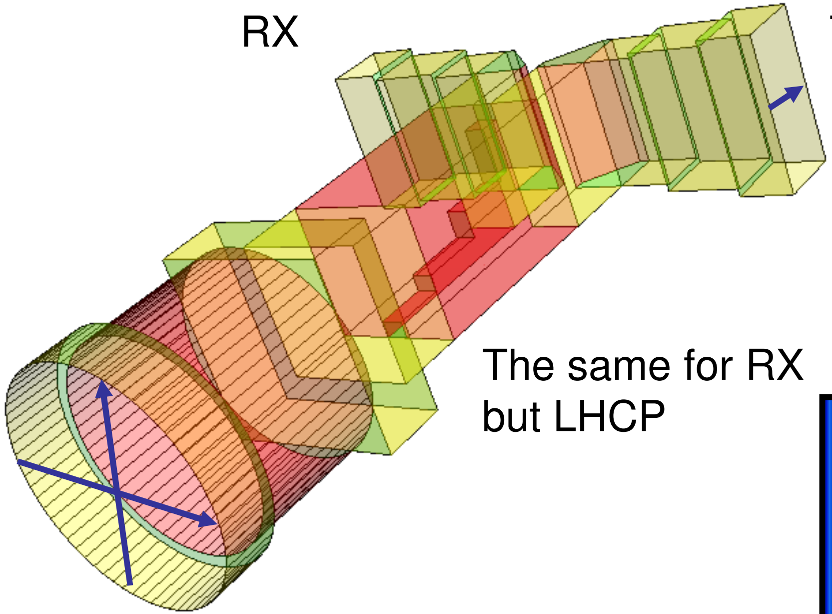




OMT – CIRCULAR POLARIZATION

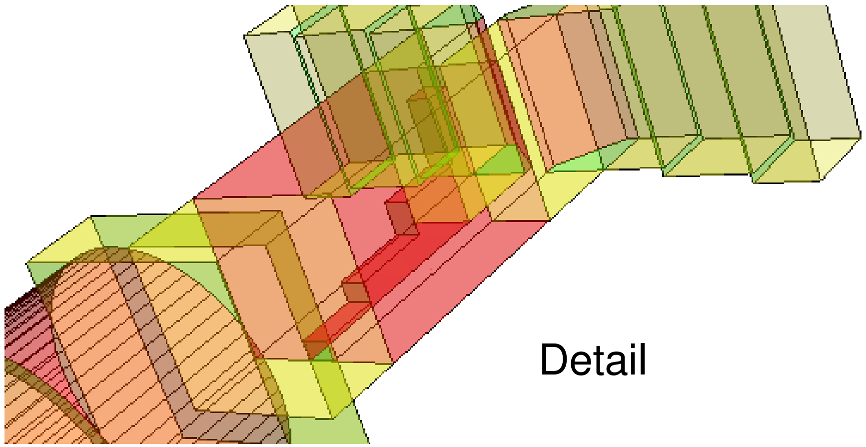
RX

TX

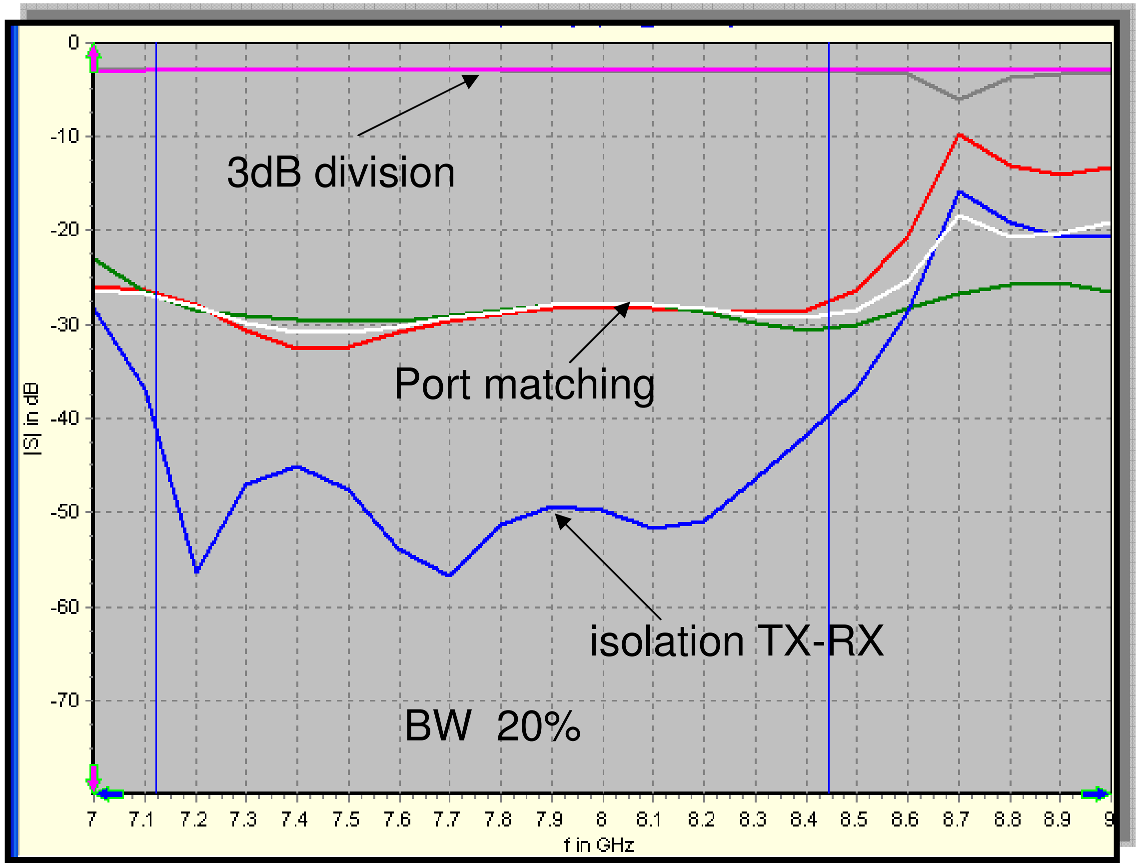


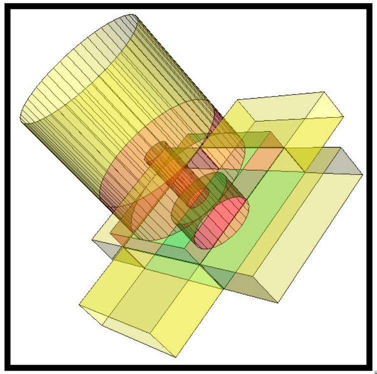
The same for RX but LHCP

3dB with phase-shift of +90º (RHCP)



Detail





Turnstile Junction

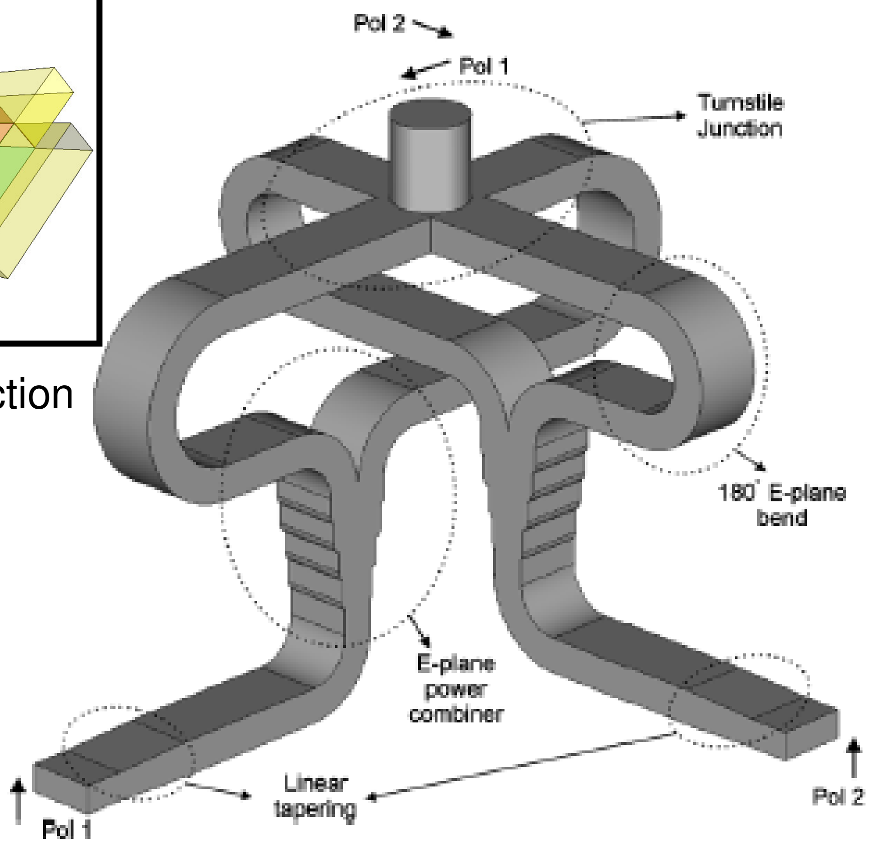
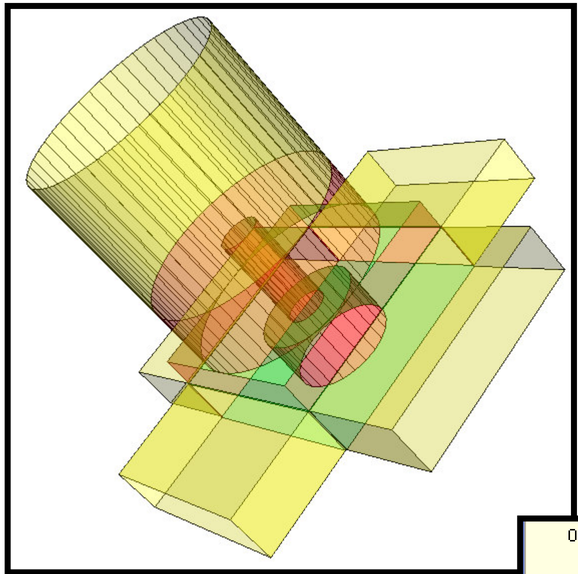


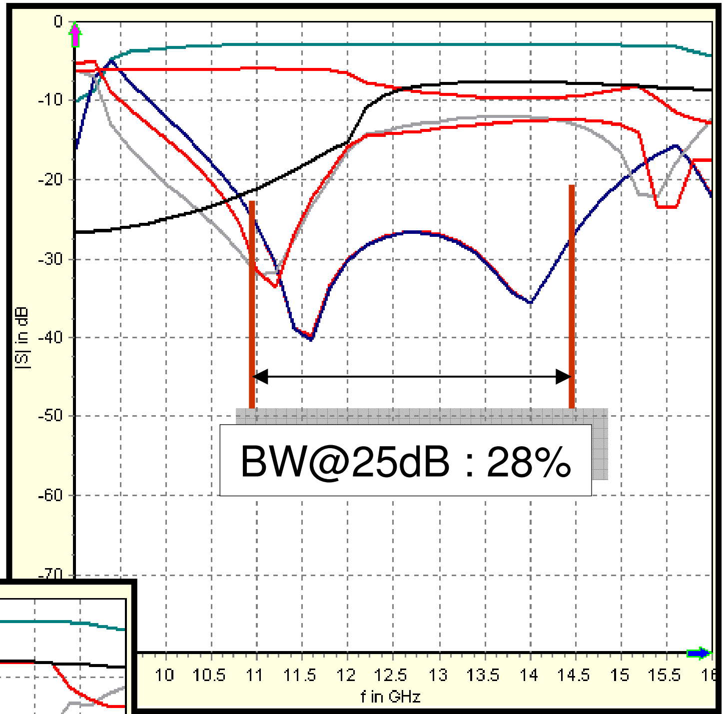
Fig. 3. Internal view of the full OMT. Opposite ports of the turnstile junction are brought together with E-plane bends and power combiners.

Navarrini et al.
"*A Turnstile Waveguide Junction Orthomode Transducer*"
IEEE Trans. on MTT, jan. 2006

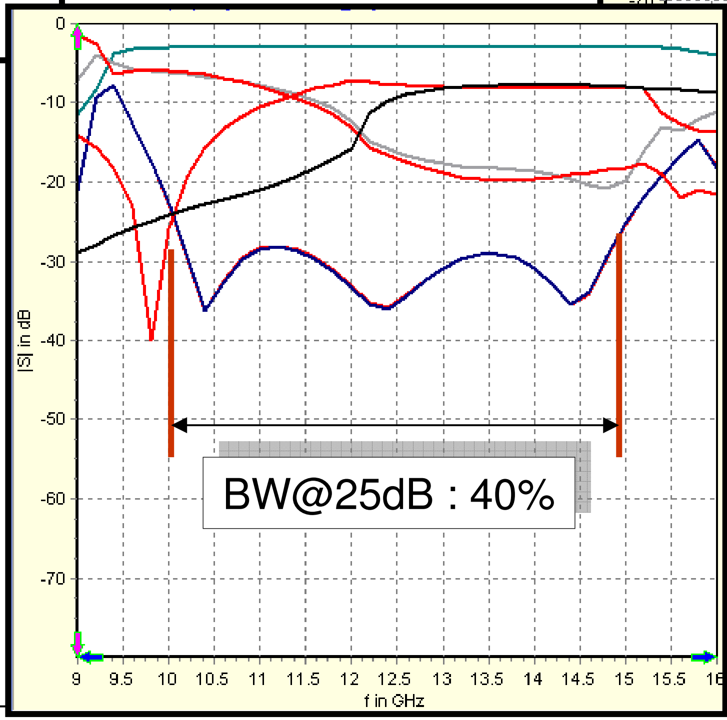
OMT – BROADBAND LINEAR POLARIZATION



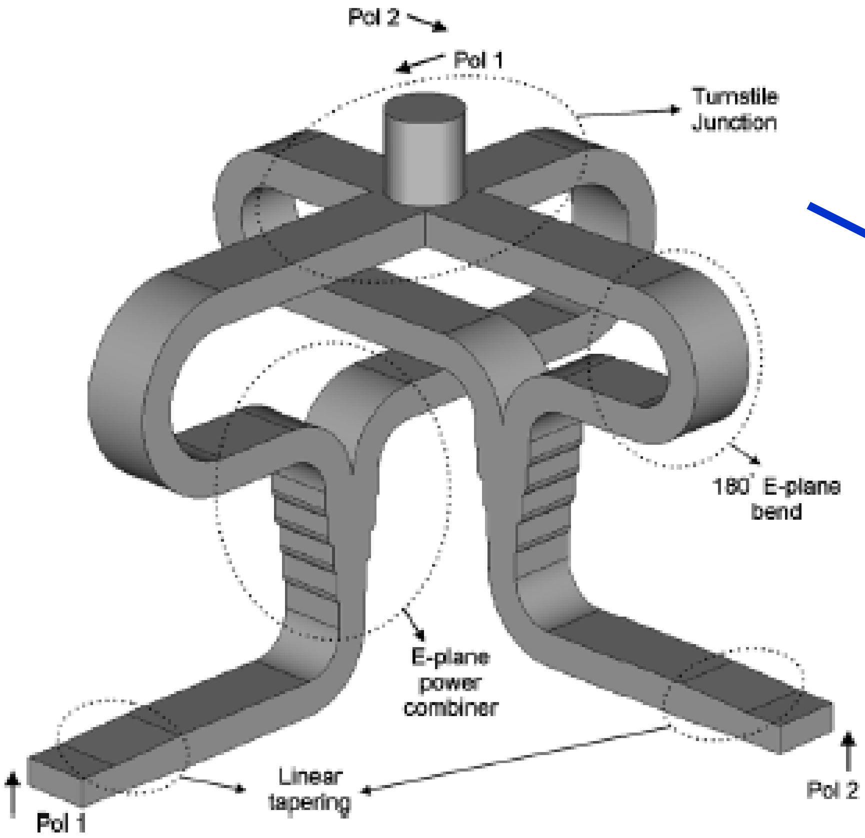
Isolation > 50dB
Typ. 60dB



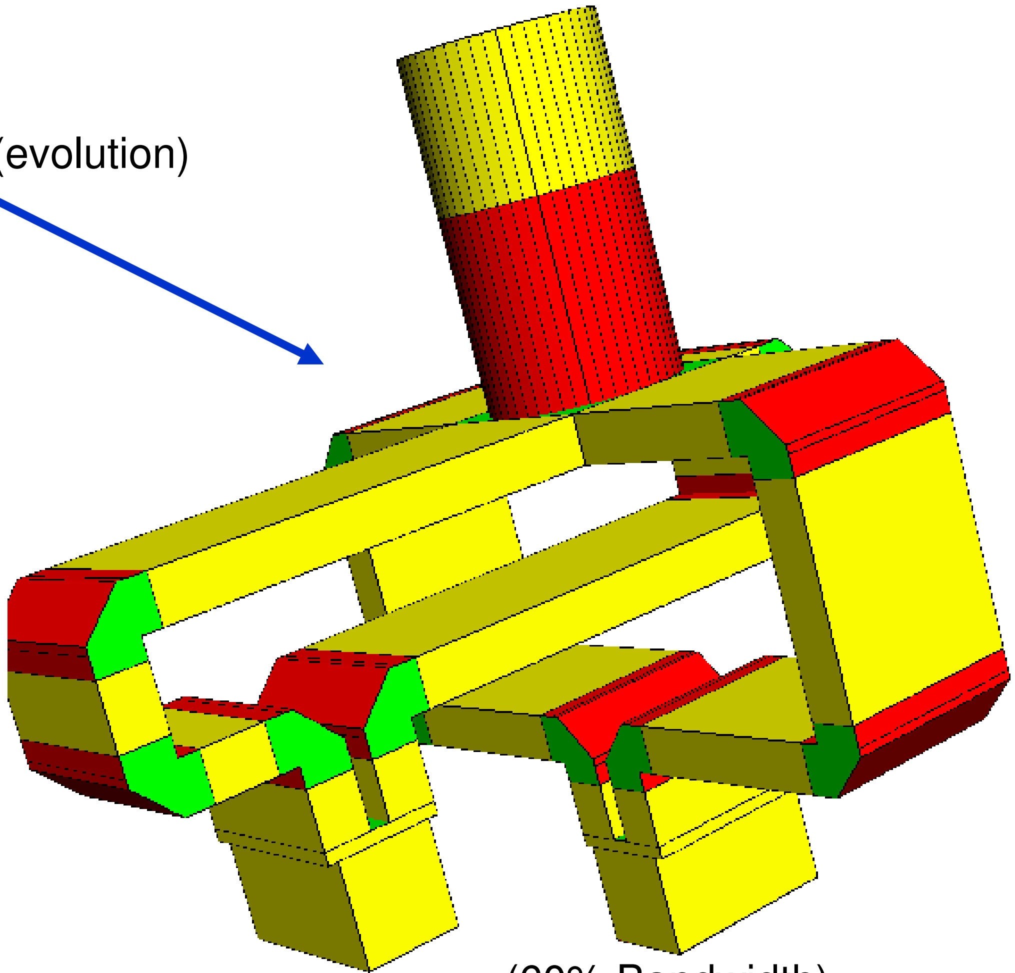
We can do better



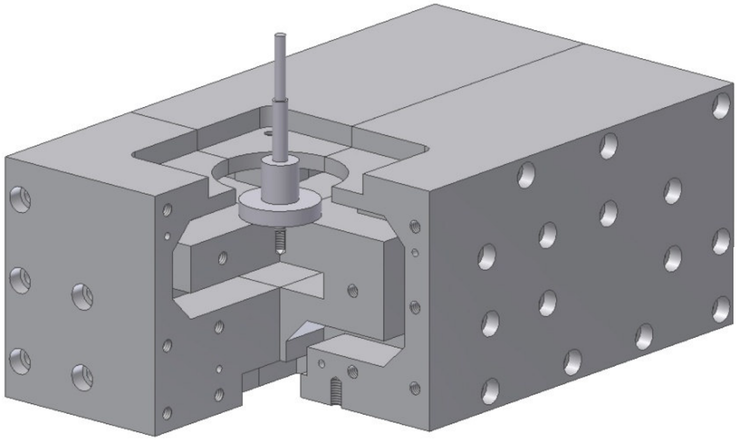
Turnstile Based

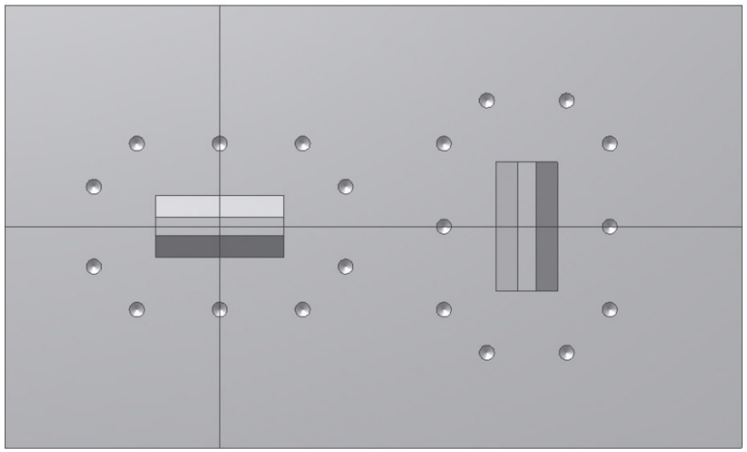


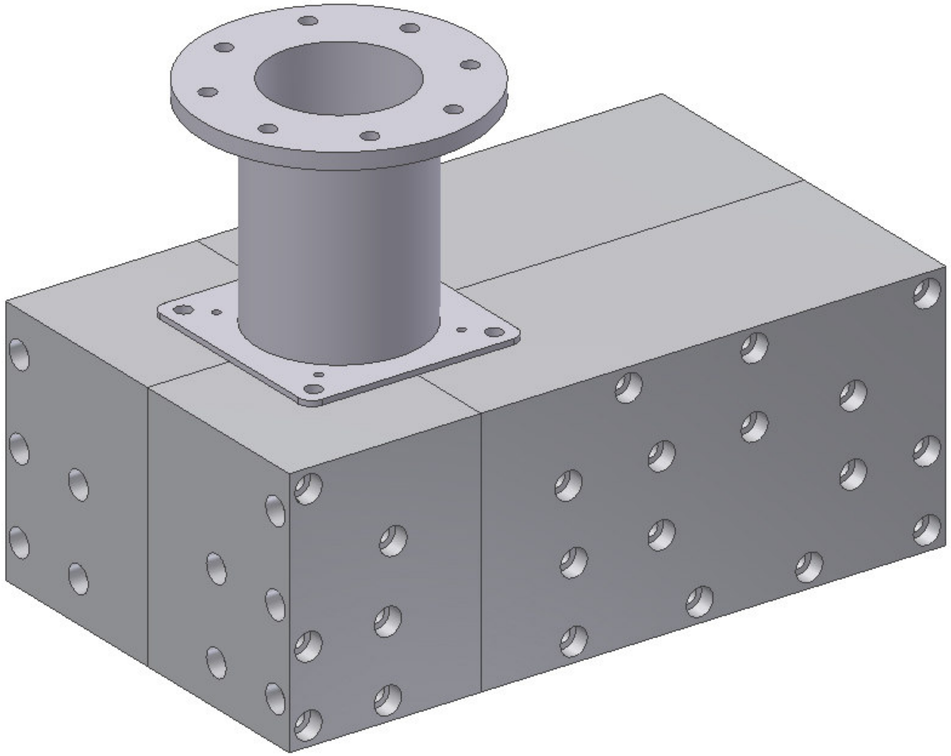
(evolution)



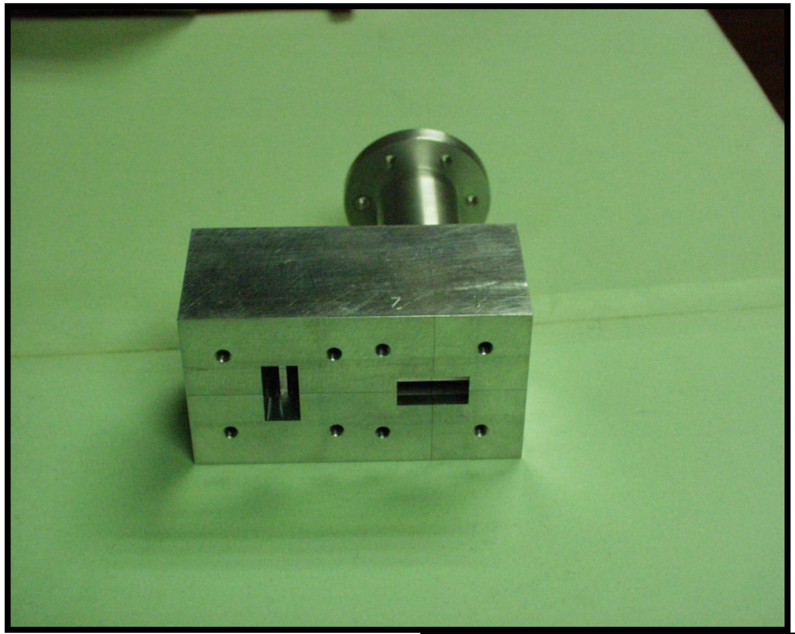
(60% Bandwidth)

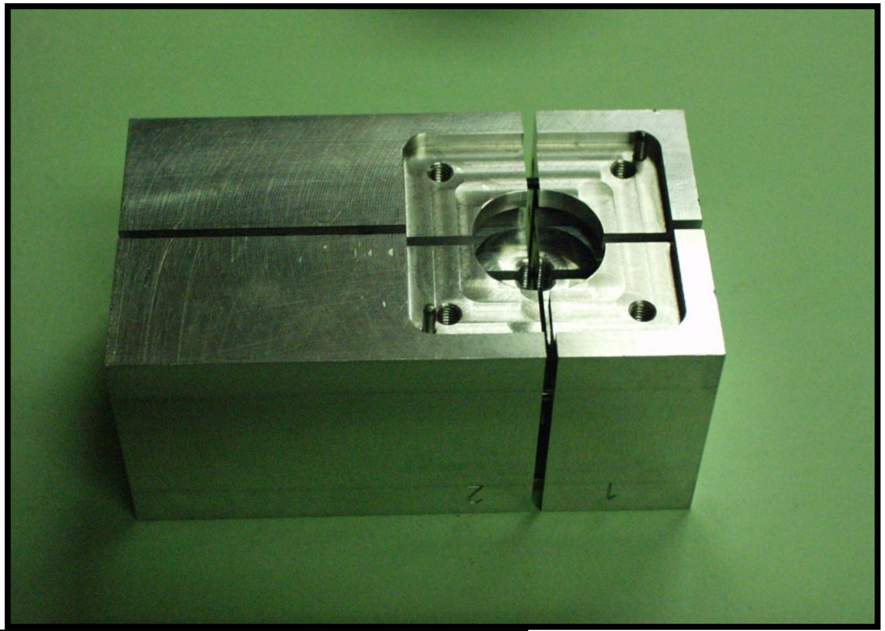


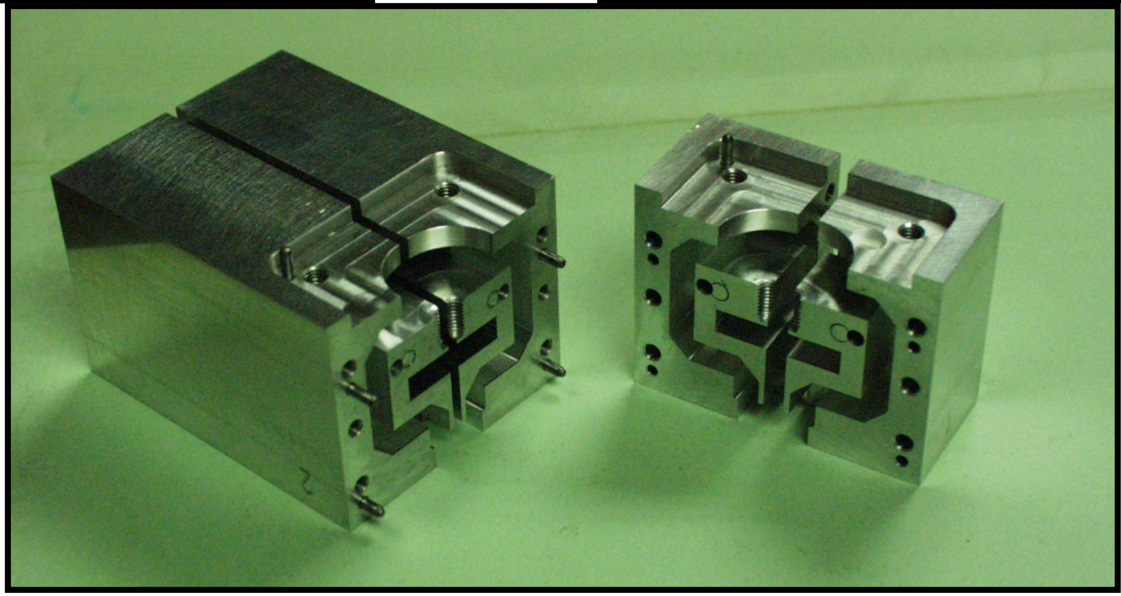




OMT – BROADBAND LINEAR POLARIZATION

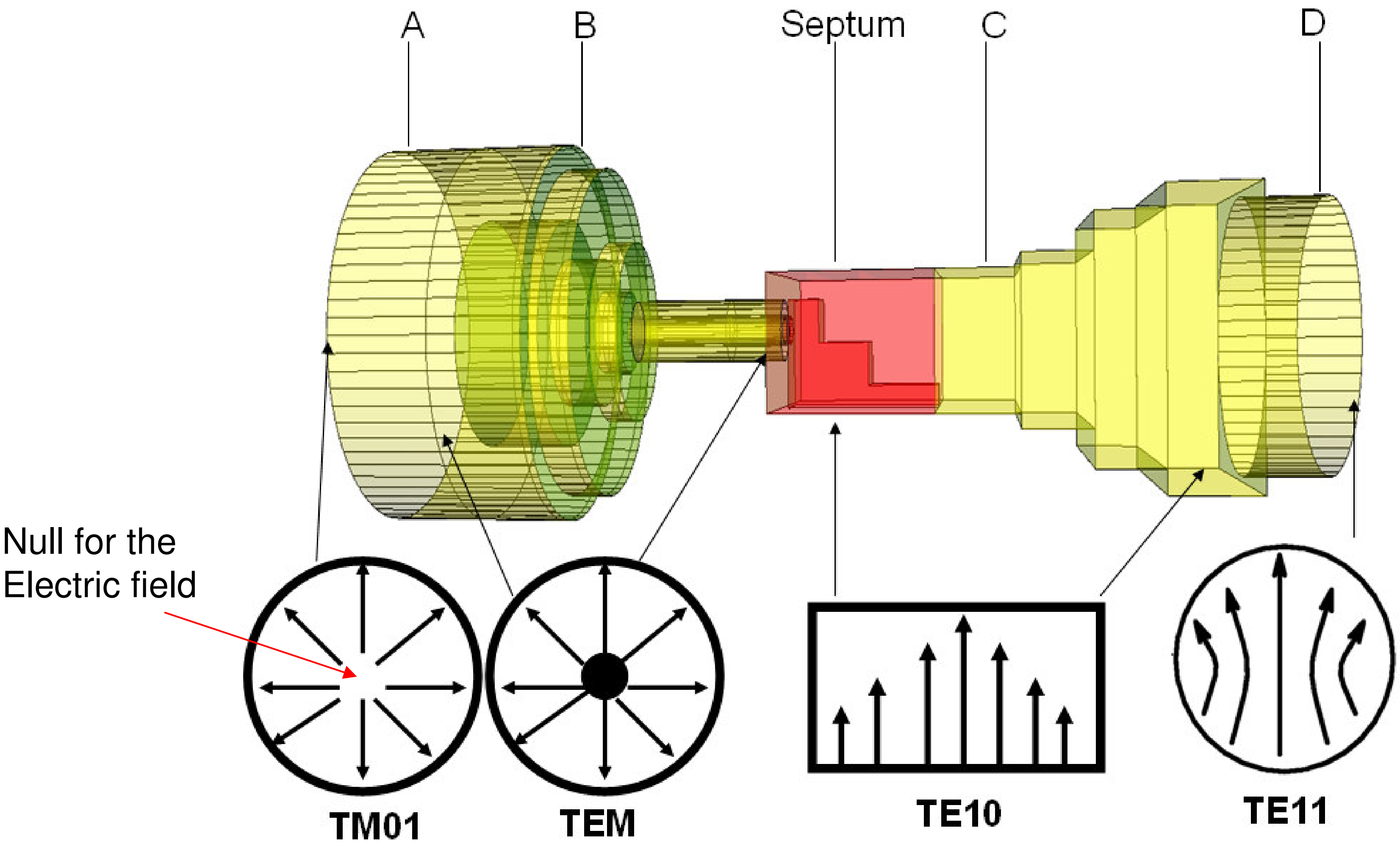




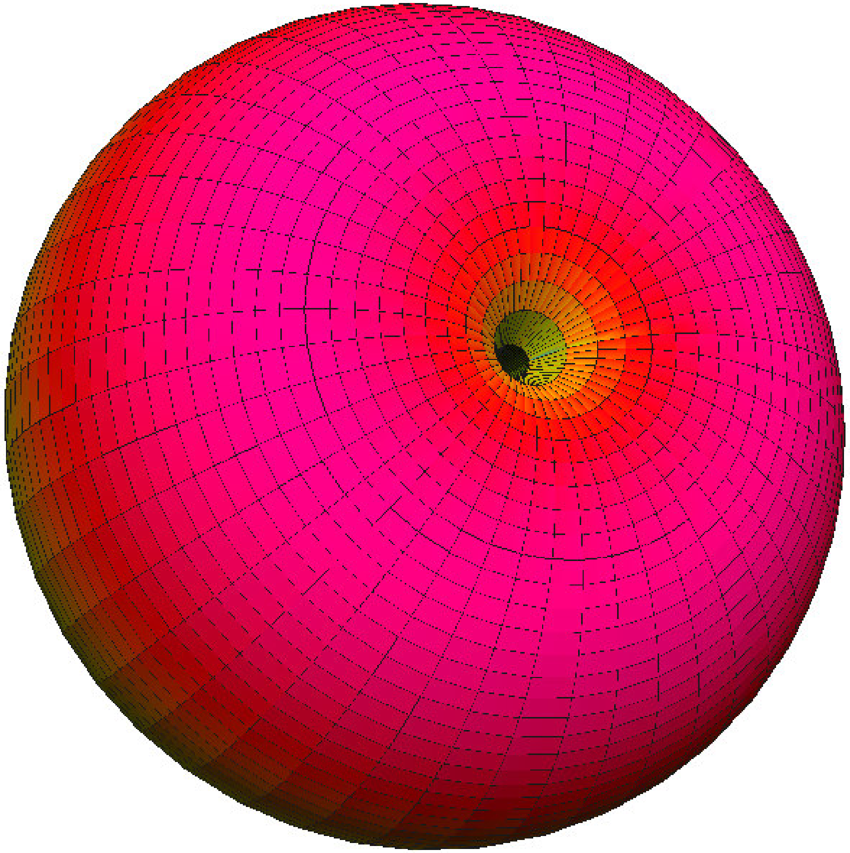


Transition from "a traditional circular TE11" to a "special circular TM01"

→ TM01 mode: <u>null for the electric field</u> along the waveguide axis to conduct electron beams or circuitry

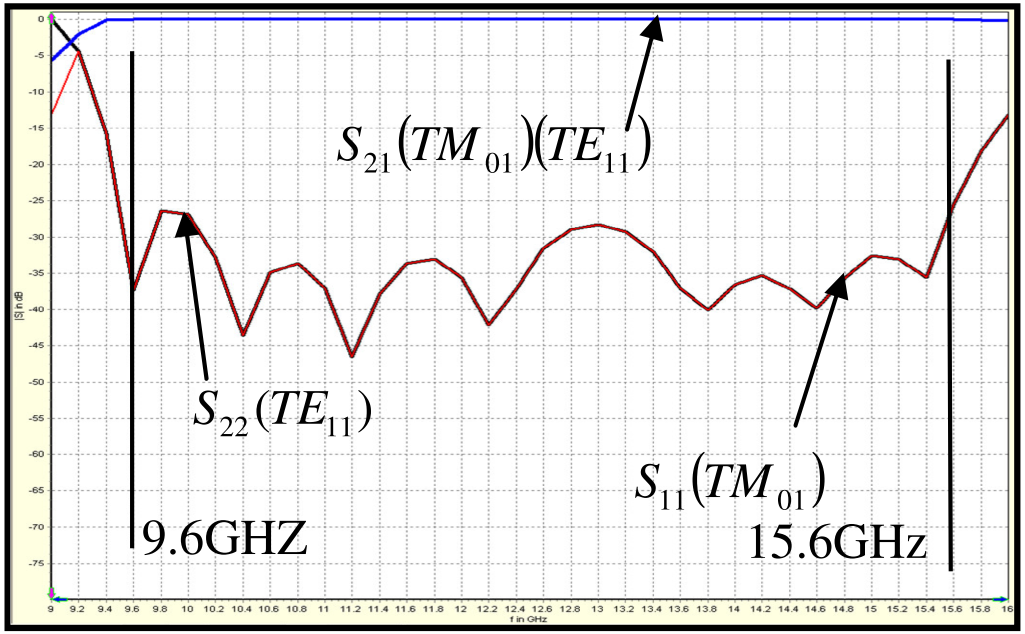


MODE CONVERTER TE11 to TM01



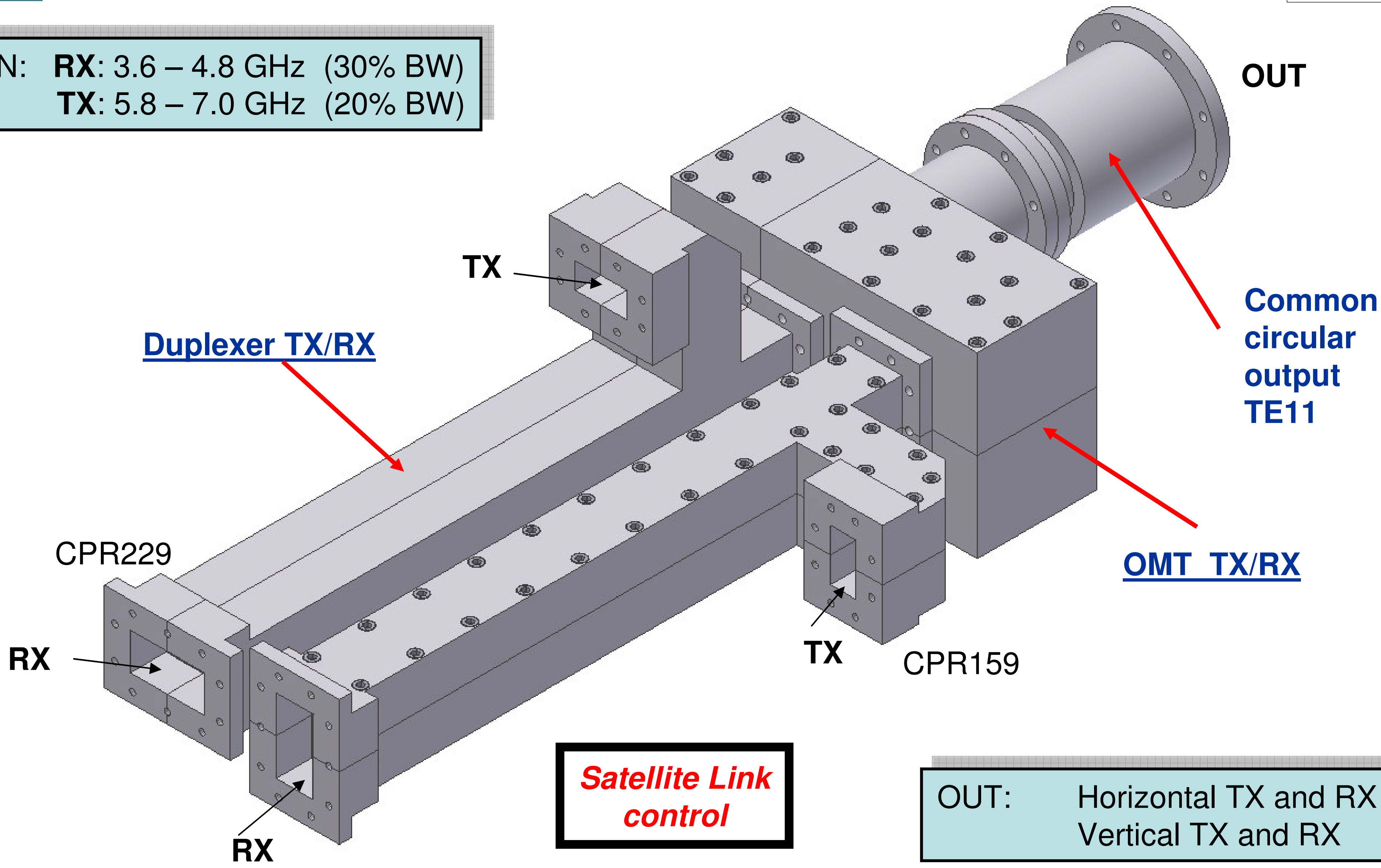
Radiation Diagram for the TM01 mode

BW: 50%



C-band FOUR-PORT RECEIVER / TRANSMITTER

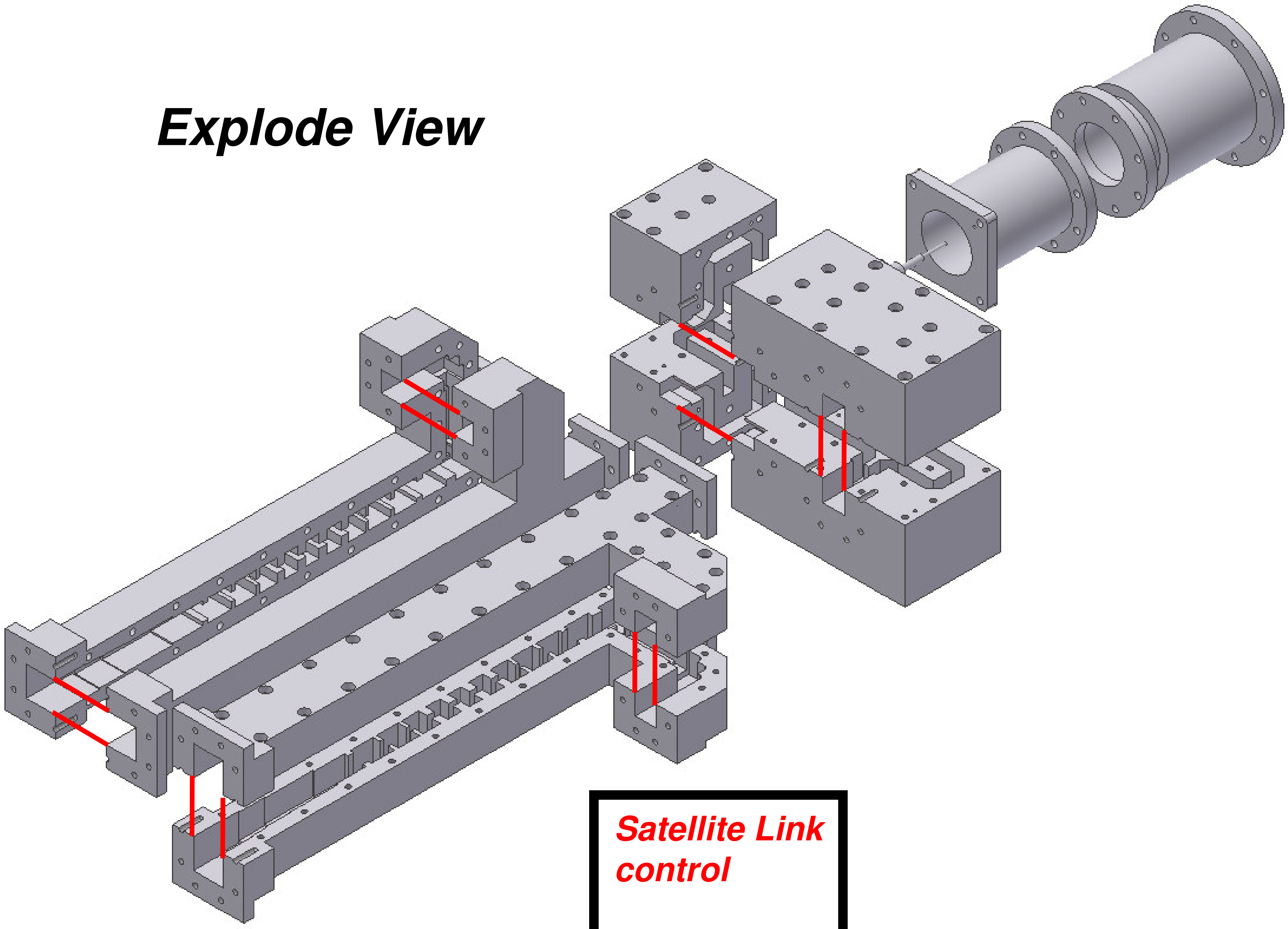
IN: **RX**: 3.6 – 4.8 GHz (30% BW)
TX: 5.8 – 7.0 GHz (20% BW)



Satellite Link control

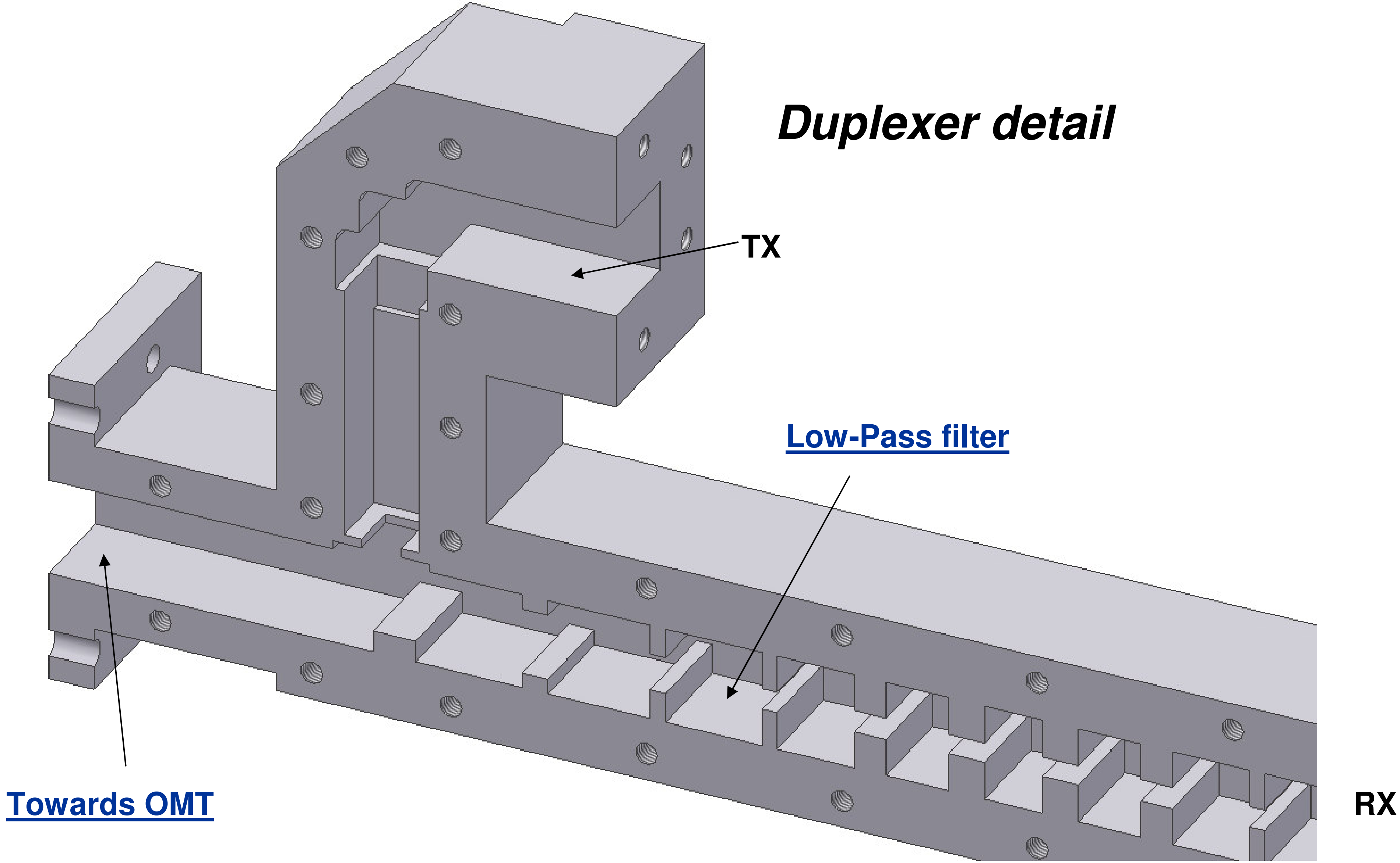
OUT: Horizontal TX and RX
Vertical TX and RX

Explode View

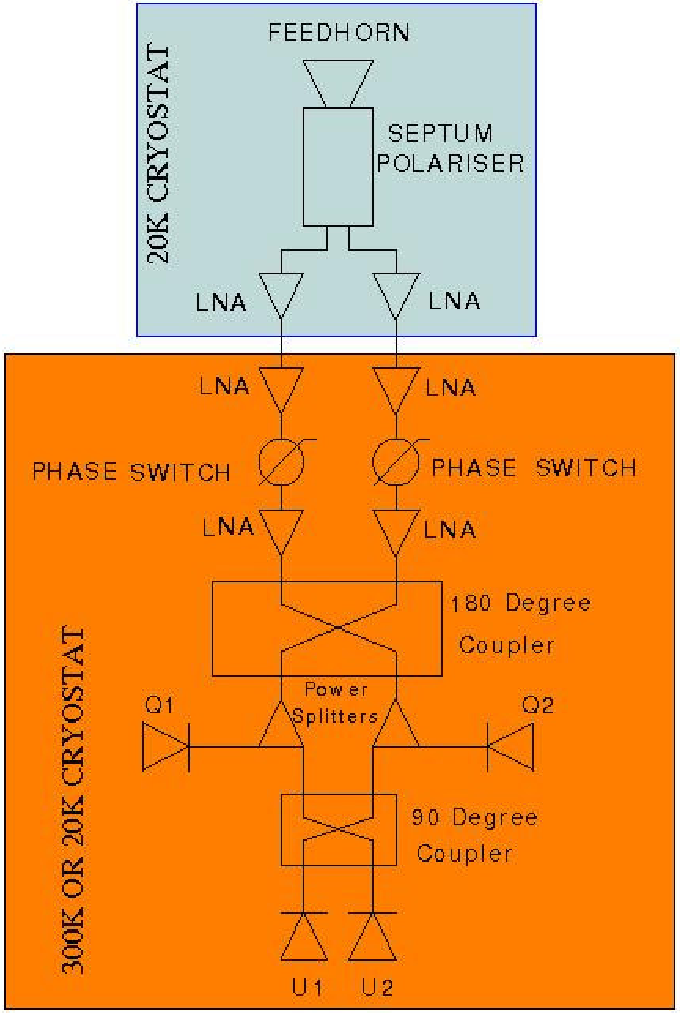


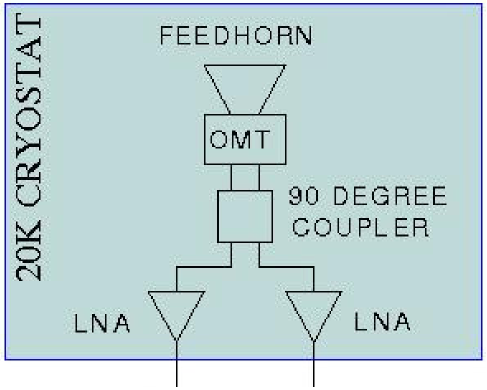
Satellite Link control

Duplexer detail



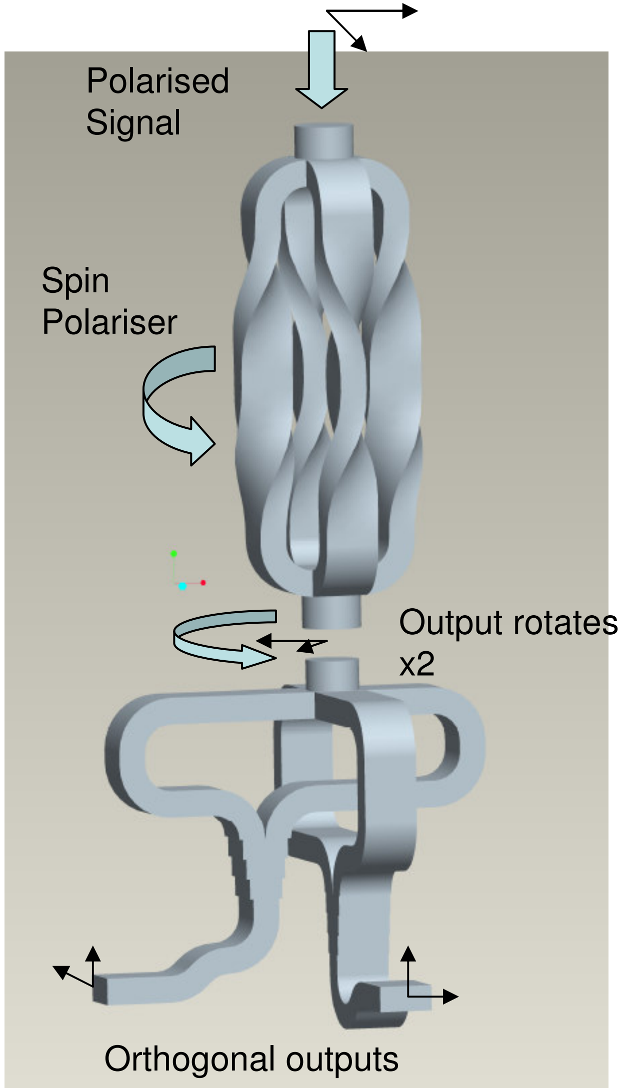
Measure the degree of Circular Polarization existing in the Cosmic microwave radiation.



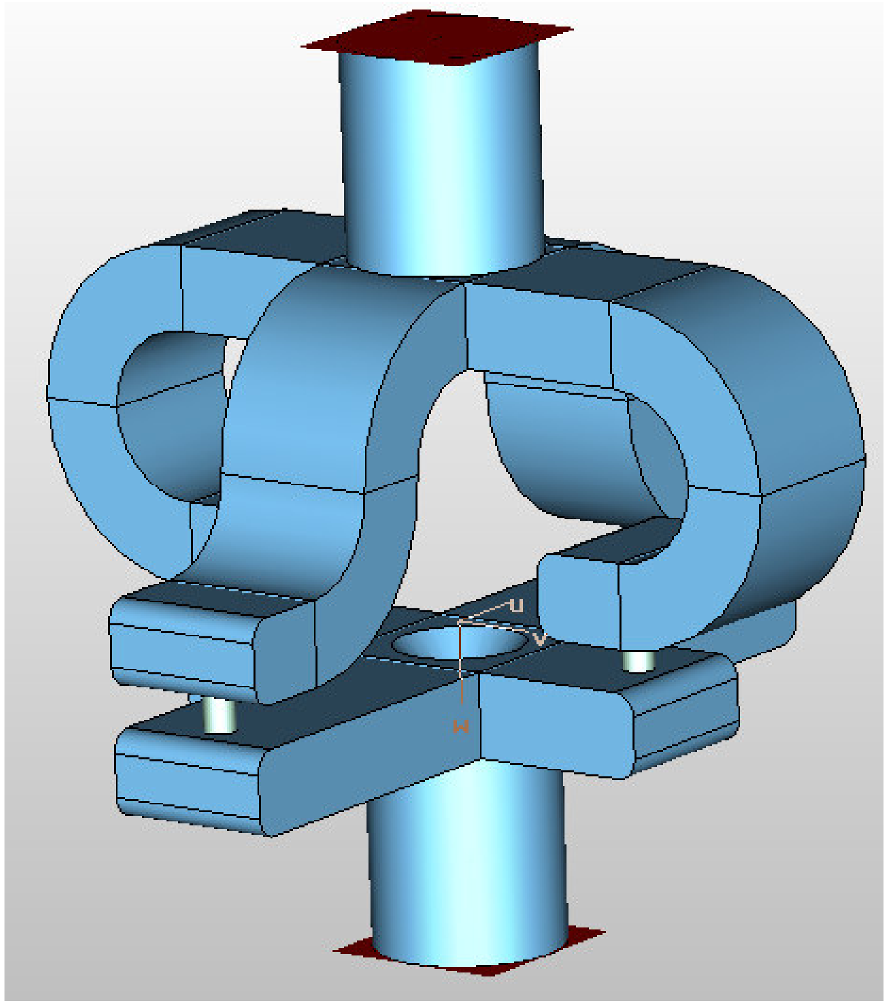


Alternative Broadband

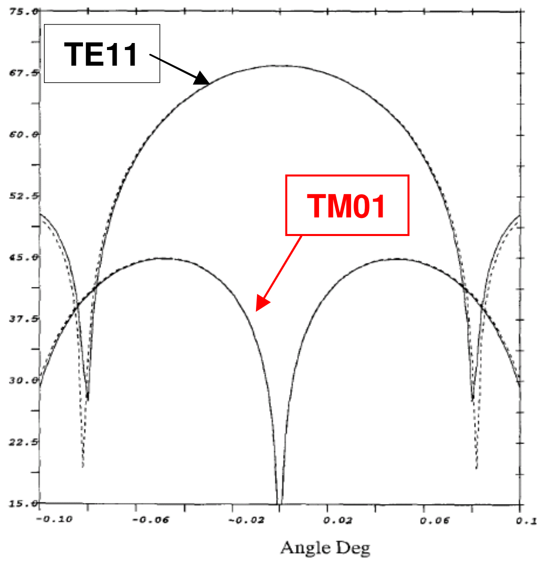
System using 2 turnstile at 45º and 180º phase shifters

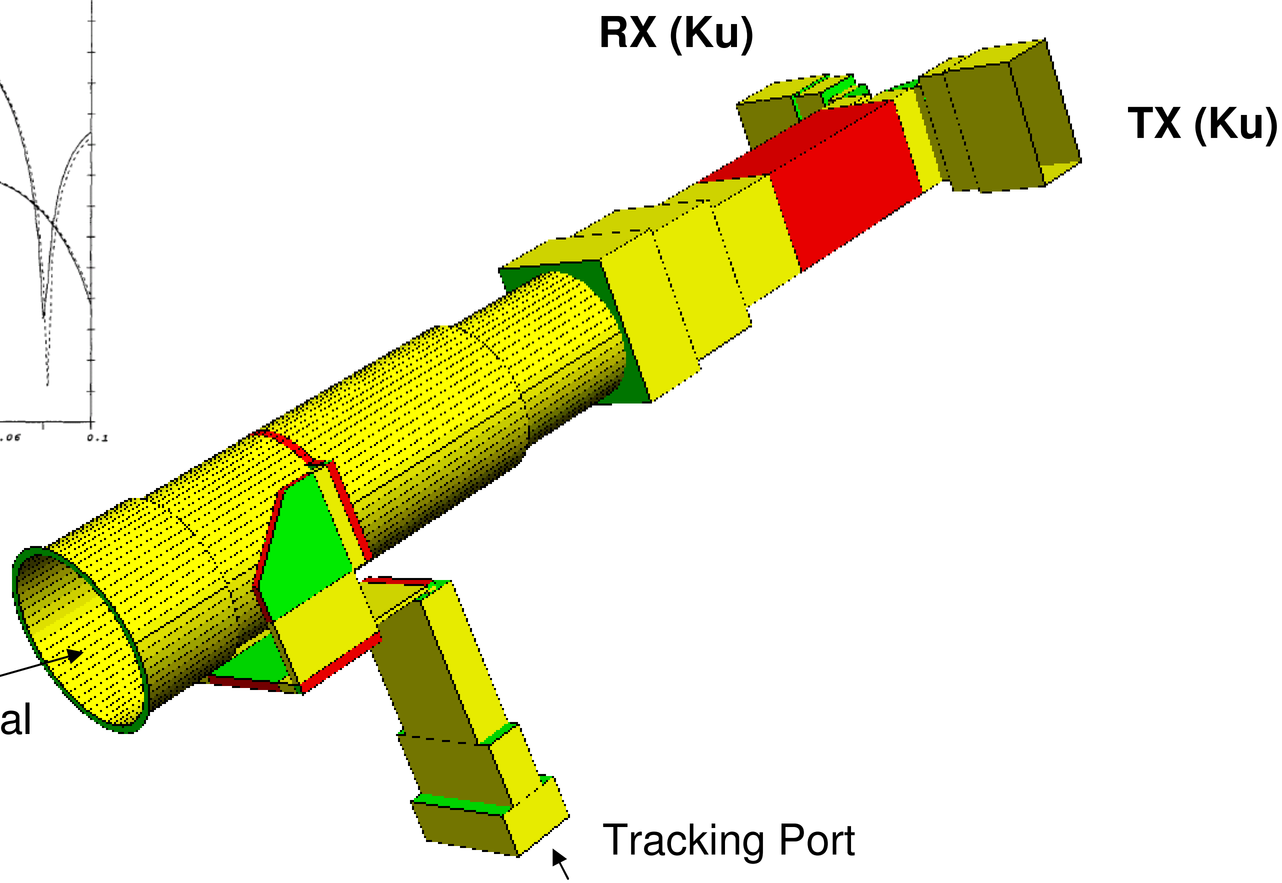


Alternative using Coaxial Probes



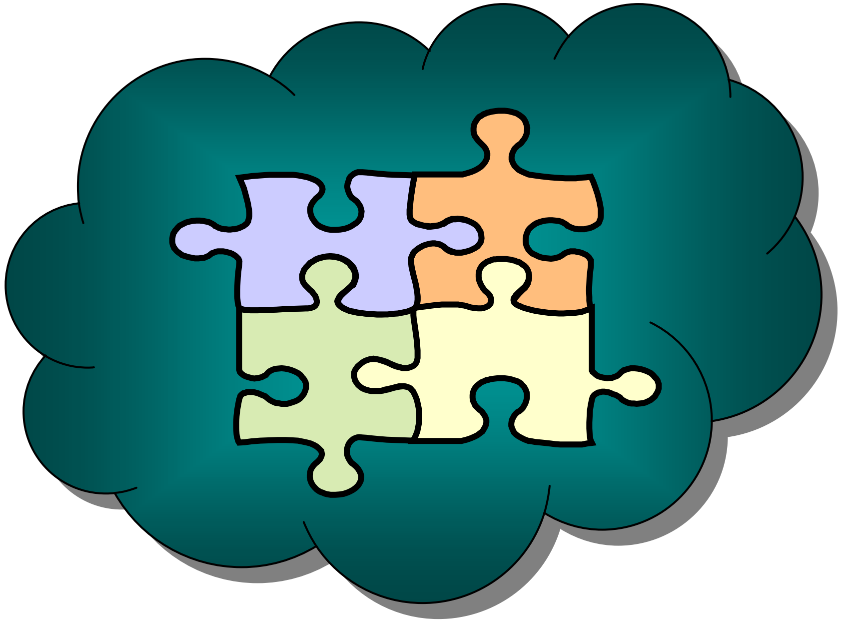
Radiation diagram





(Towards the antenna)

TE11 mode: Useful signal
TM01mode : Tracking



Limit is our Imagination