Evanescent mode coupling in coaxial HOM filters

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Acknowledgments:
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ICFA Workshop on High Order Modes in Superconducting Cavities 2025
DESY, Hamburg, Germany - 6-8.10.2025

[1]BTU Cottbus and FBH, [2]CERN, [3]Lancaster University, [4]University of Rostock

INTRODUCTION

Introduction

Some thoughts on the course of history

COUPLERS, TUTORIAL AND UPDATE

E. HAEBEL

CERN, Geneva, Switzerland

First a tutorial on couplers is given. Describing the coupling effect in the form of an equivalent generator

One could now dream of a computerized synthesis procedure which takes the mode frequency distribution and the required Q_{ex} values as input, calculates the equivalent quantities I_0 and C_s for a given probe geometry and position, selects a network structure and calculates its optimal element values.

Especially one item in this list is still very much in the realm of intuition and experience. It is the selection of a suitable network.

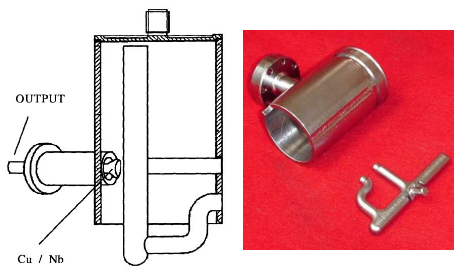
[E. Haebel, Part. Accel. 40, 141 (1992)]

Introduction

Some thoughts on the course of history

- Era of Numerical simulations tools yield a zoo of coaxial HOM couplers but ...
  - Choice a suitable **topology** remains doubtful
  - **Systematic design** typically based on exhaustive parameter variations
  - Black box behavior hinder in understanding the origin of particular filter characteristics (**parasitic and non-parasitic phenomena**)

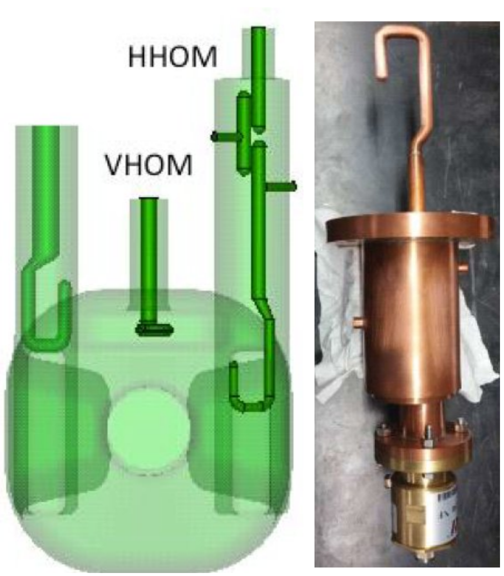

LHC HOM couplers [CERN]



J. Sekutowicz, et. al. , HERA, TESLA, ...


B. P. Xiao, et al. DQW-CC HOM Coupler,


Q. Wu, et. al., HOM Damper for 56MHz SRF Cavity for RHIC

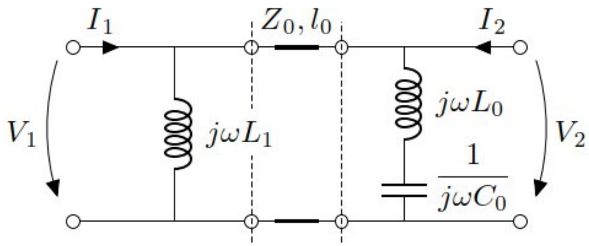


De Silvia, et al., RFD-CC HHOM Coupler

Introduction

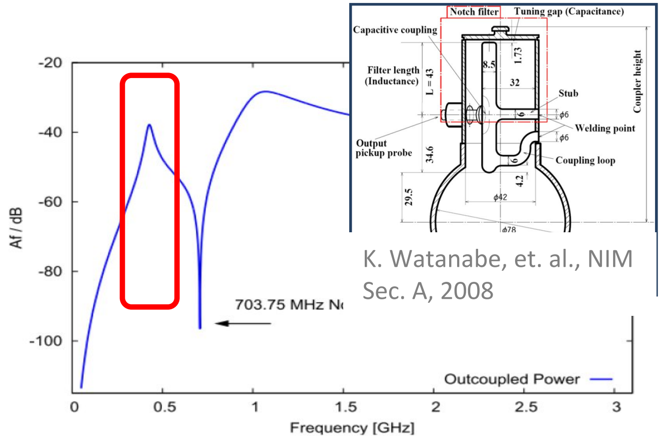
Motivation

- Common to many HOM couplers is a parasitic behavior below notch
- Notch filter seem to be placed within the pass-band of a high-pass filter
- Intrinsic property given by combination series notch filter (L_0C_0) and fixing of inner conductor (L_1)



How to avoid this combination?

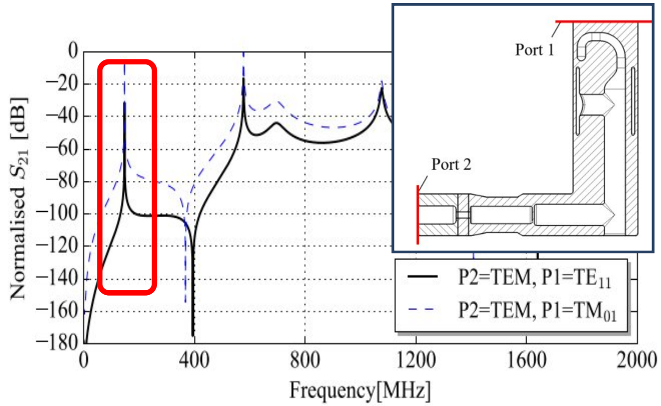
RF Transmission of modified TESLA Coupler



K. Watanabe, et. al., NIM Sec. A, 2008

W. Xu, et. al., in Proc. PAC 2011 , TUP060

RF Transmission of DQWCC HOM Coupler

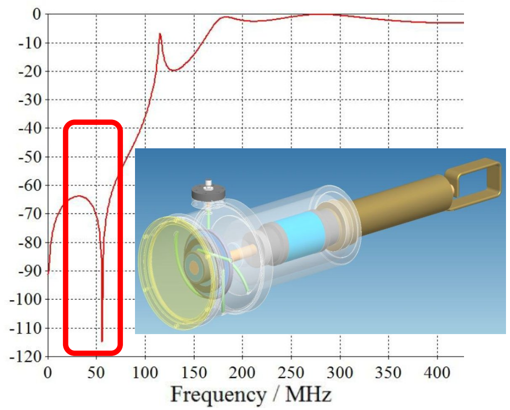


J. Mitchel, PhD thesis 2019

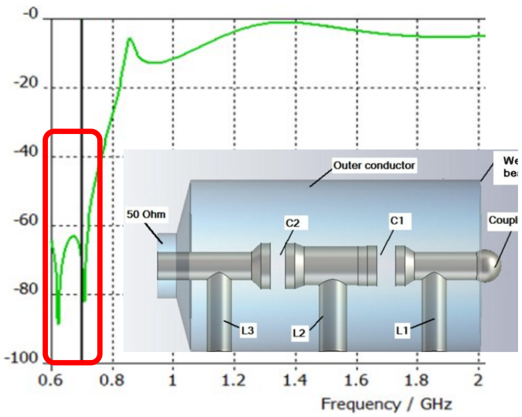
Introduction

Motivation

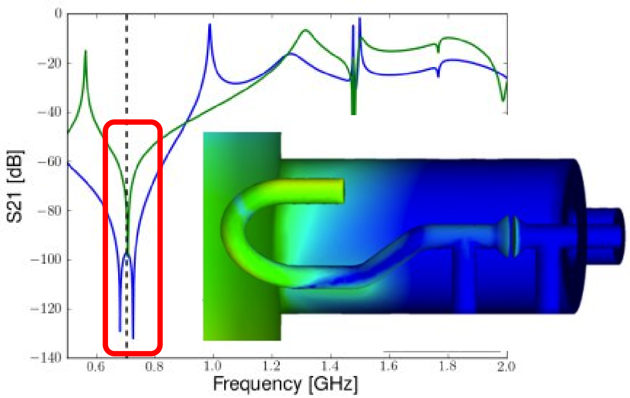
- Some HOM couplers reveal an “unusual” notch characteristic



Q. Wu, et. al., HOM Damper Design ..., BNL, 2010

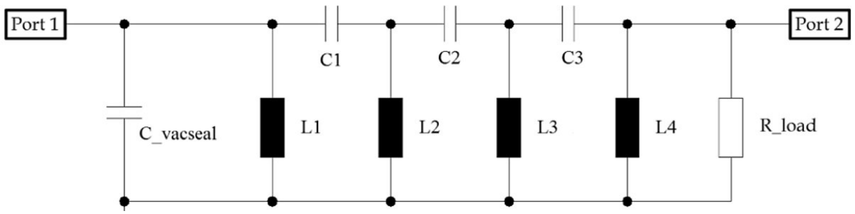


W. Xu, in Proc. PAC2011, TUP060



R. Ainsworth, in Proc. IPAC2012, WEEPPB008

- In contradiction to equivalent circuits based on alternating shunt inductance and series capacitance (only notch at **f = 0 Hz** possible)



Q. Wu, et. al., Operation of the 56 MHz superconducting rf cavity in RHIC with higher order mode damper, PRAB 22, 102001 (2019)

What is the origin of the notch(es)?

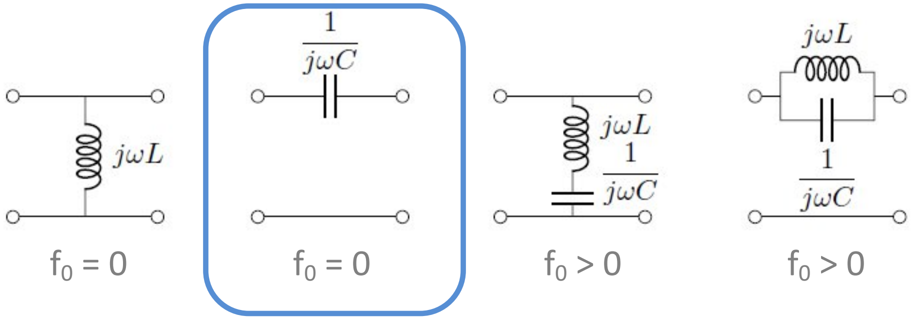
Towards an understanding of the “unusual” notch in coaxial lines

PHENOMENOLOGICAL INVESTIGATIONS

Phenomenological investigations

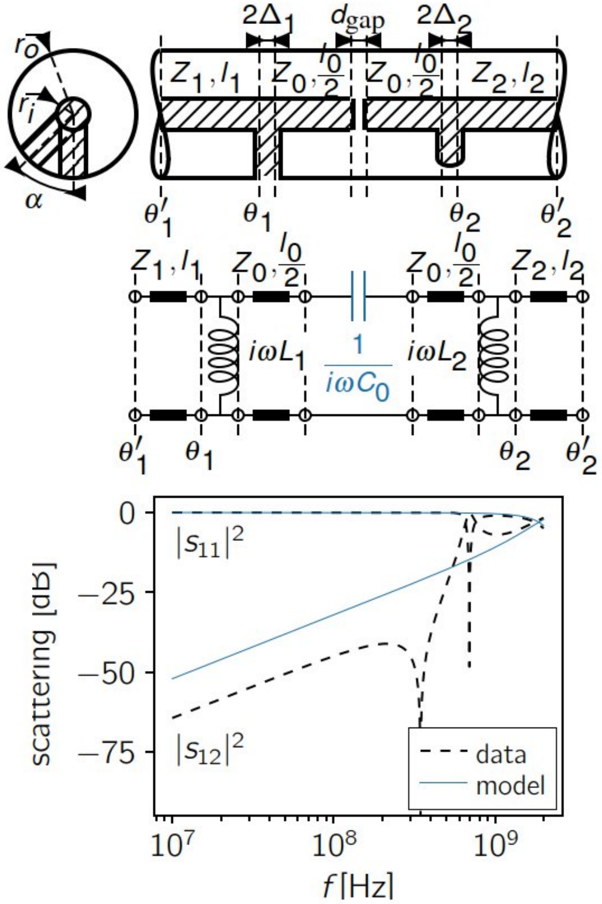
Topology, filter components, and equivalent circuits

- Analysis of waveguide obstacles and discontinuities by numerous model fits
- Focus on elements that are appropriate for high-pass filters, i.e. equivalent behavior of:



- Ladder of shunt inductance and series capacitance will **NOT** introduce a notch at a frequency > 0

Coaxial guide with capacitive gap between two inductive posts



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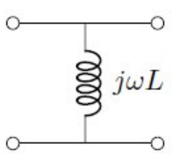
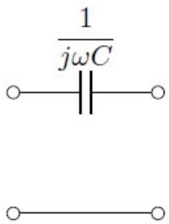


$f_0 = 0$



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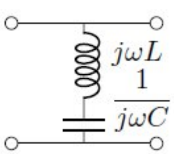
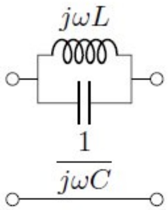


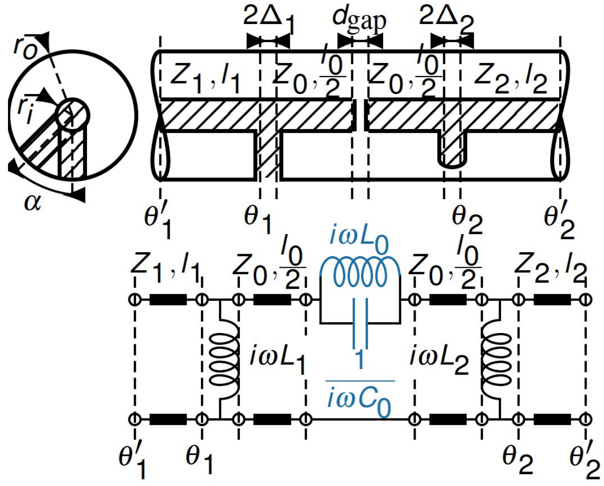
$f_0 > 0$

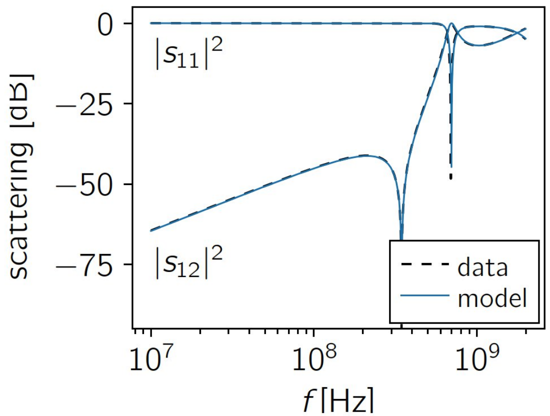


$f_0 > 0$

- **Parallel LC resonator** yield perfect match between equivalent circuit model and simulation data over large frequency range

Coaxial guide with capacitive gap between two inductive posts



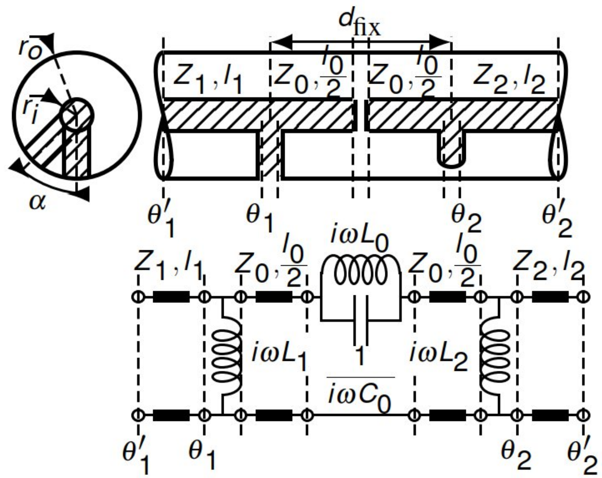


Phenomenological investigations

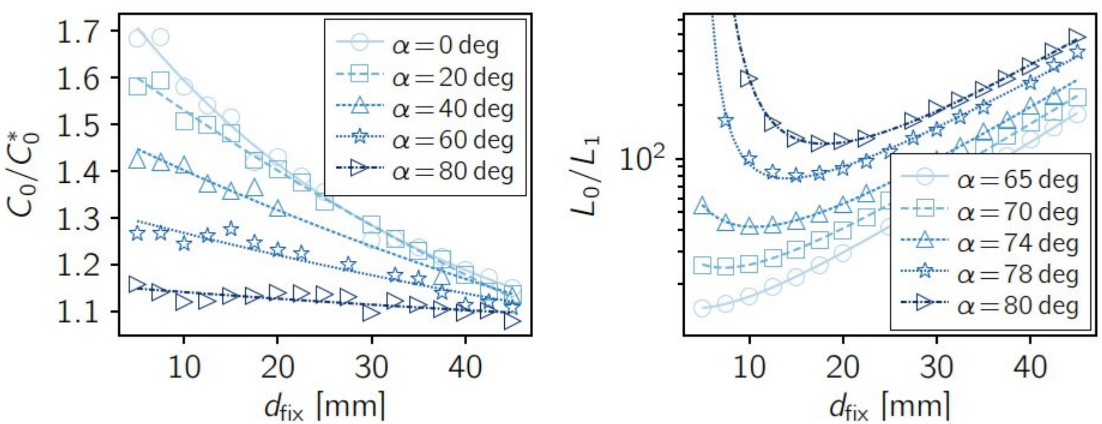
Equivalent circuit and element characteristics

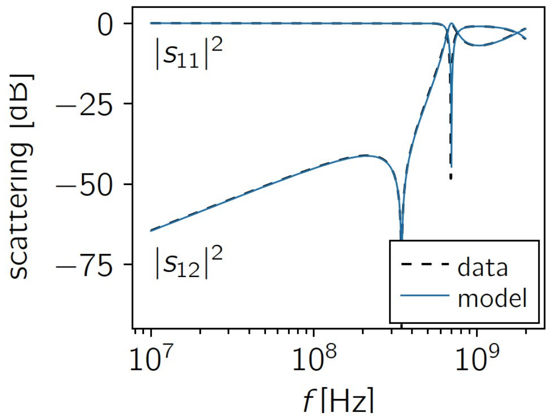
- **Canonical 3rd-order high-pass** filter with finite transmission zero at $\mathbf{f_0 >= 0}$
- Remarkable **variation of L_0** by orders of magnitude with d_{fix} and α
- L0 nearly constant over large frequency well above notch frequency -> **broad band character**
- **Indicators for coupled evanescent modes**

Coaxial guide with capacitive gap between two inductive posts



Dependency of notch filter elements

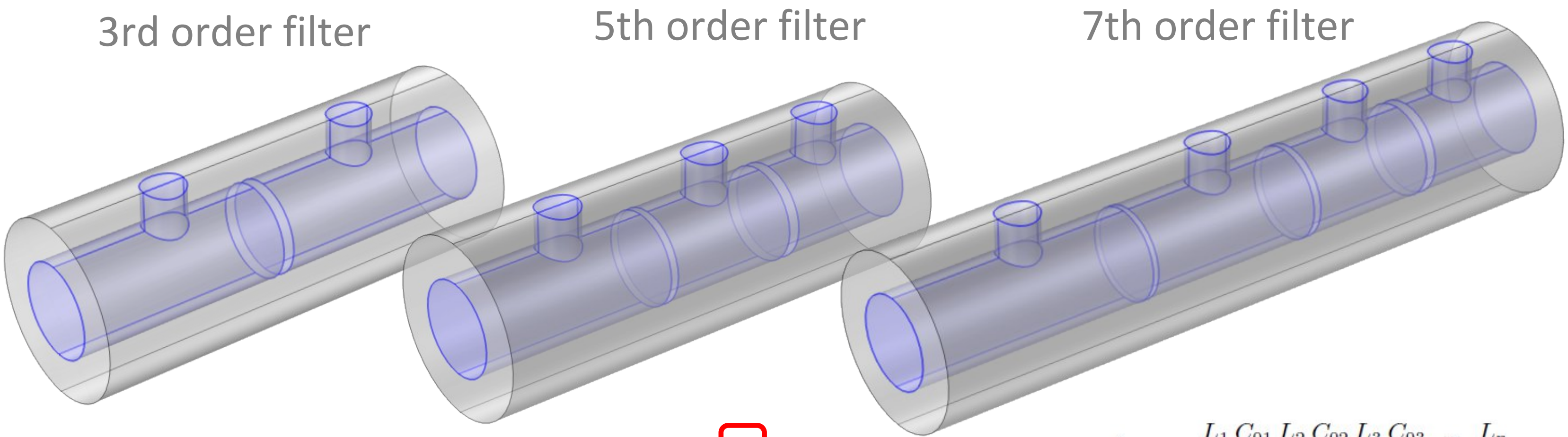


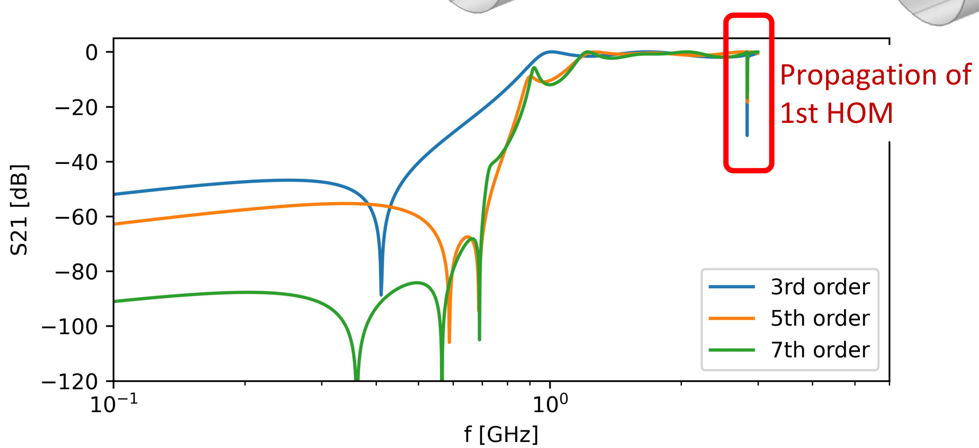


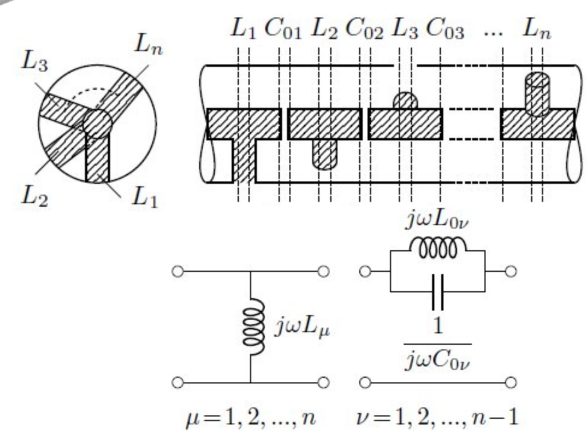
Phenomenological investigations

Scalability of the filter order

- Repetition of “T”-element **in part** analog to repetition of alternating shunt inductance and parallel LC resonator in series







Phenomenological investigations

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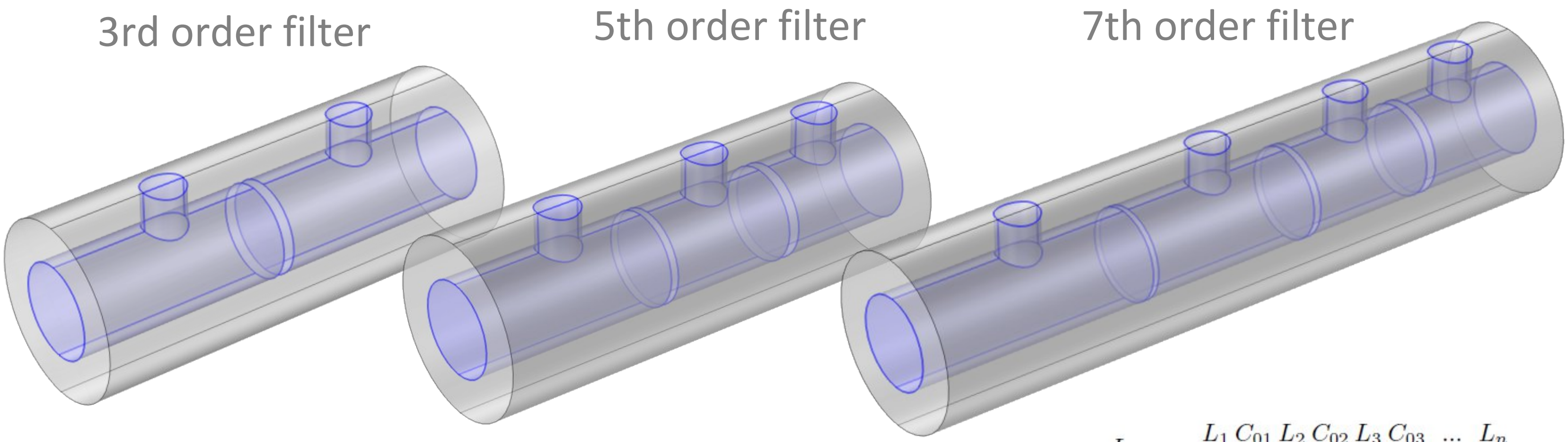
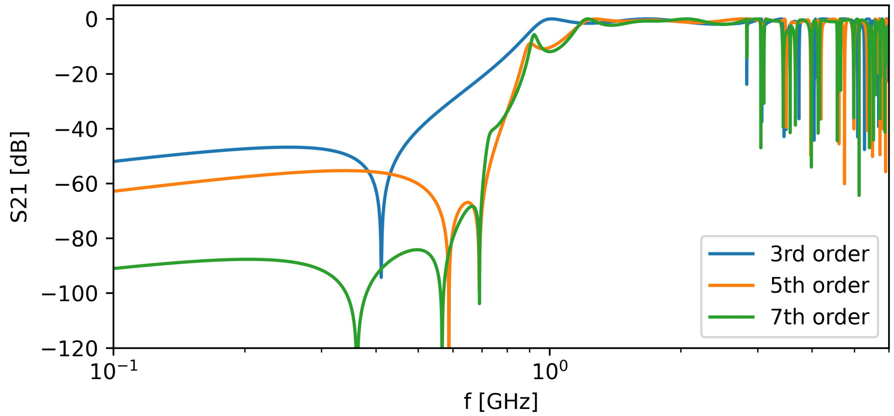
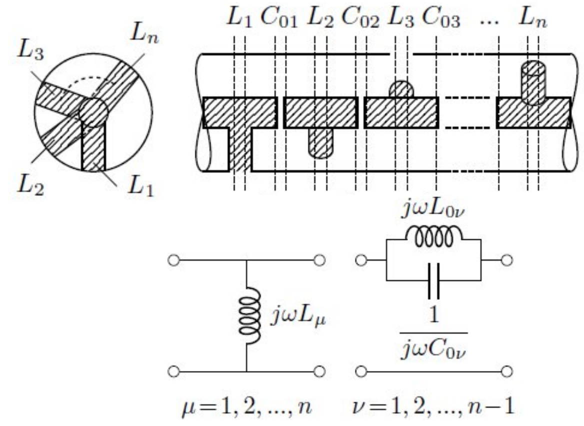






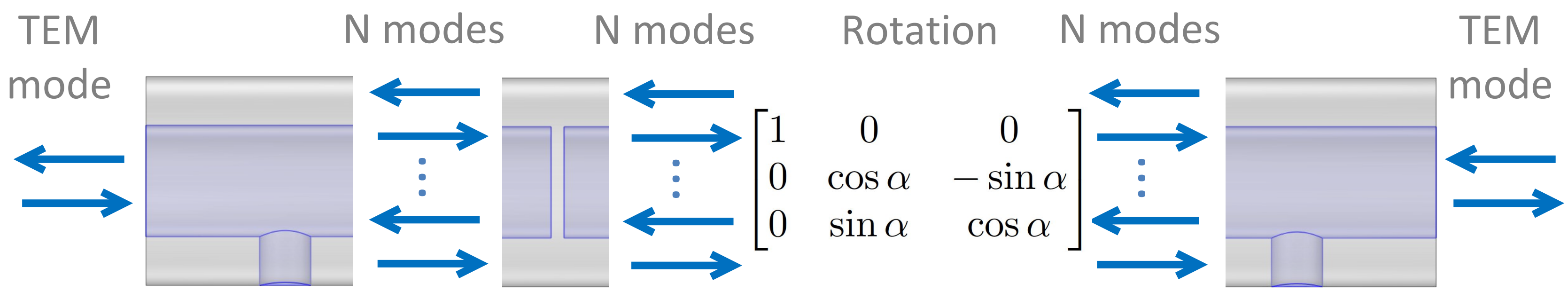
On the interference of evanescent modes in coaxial wave guides

FIELD ANALYSES

Field analyses

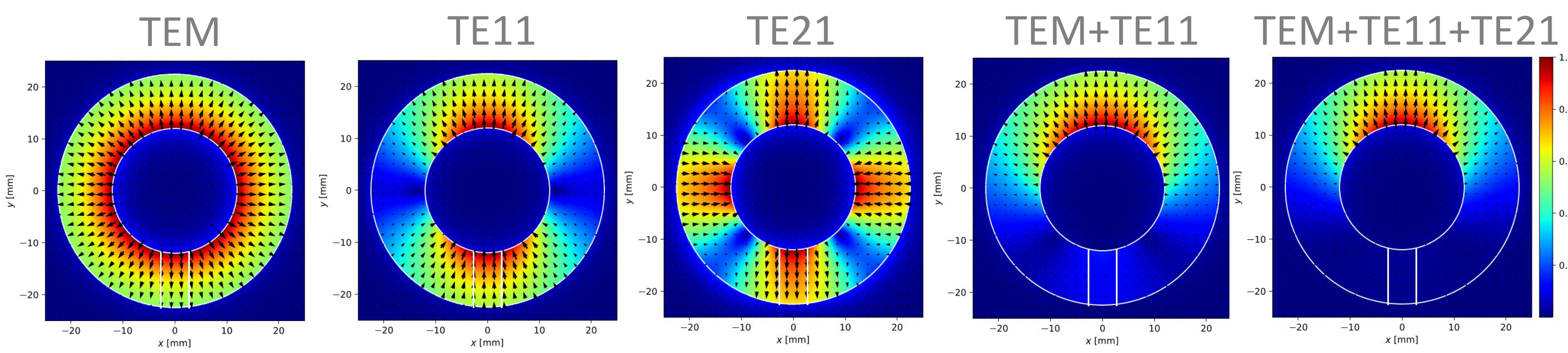
Exploration of contributing modes

- Concatenation procedure based on scattering properties (CSC)[1]



$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix}$$

- Excited modes and their superposition at a single inductive post



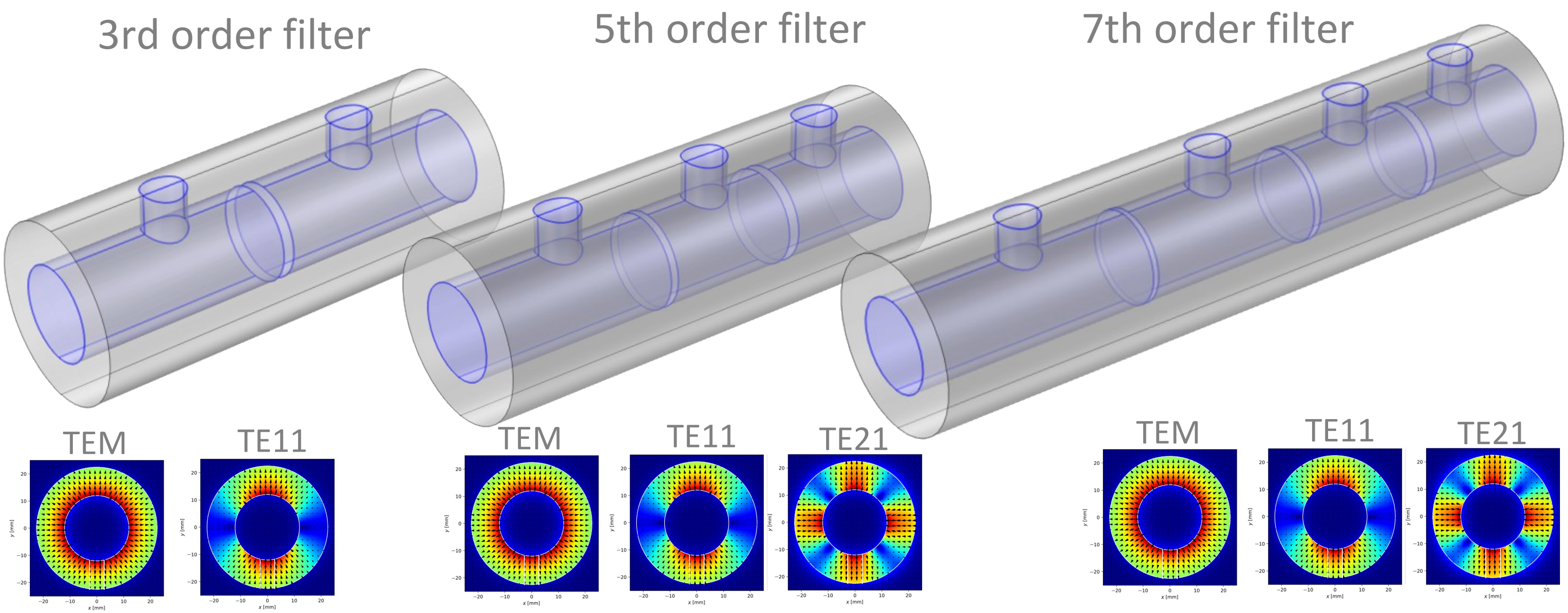
- Inductive post defines polarization angle of the excited TEmn mode

[1]H.-W. Glock, et. al., CSC—A Procedure for Coupled S-Parameter Calculations, IEEE Transaction on Magnetics, Vol. 38, No. 2, 2002

Field analyses

Properties related to the coupling of evanescent modes

- Presence of modes depends on filter order



- Coupling of evanescent modes vanishes if orthogonality applies
  - @ α=45deg, Inference of TE21 disappears below its cutoff
  - @ α=90deg, Inference of TE11 disappears below its cutoff

-> Parallel LC resonator reduces C in equivalent circuit

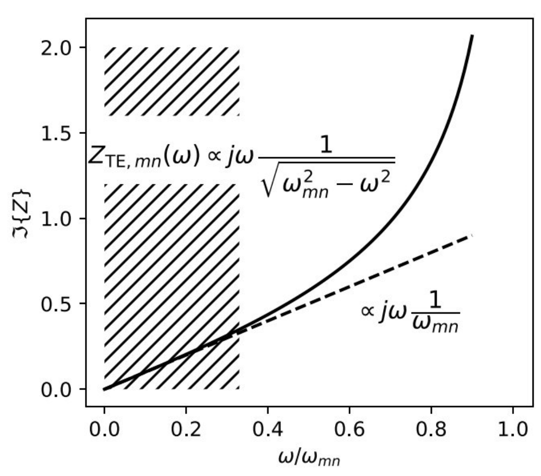
Field analyses

Properties related to the coupling of evanescent modes

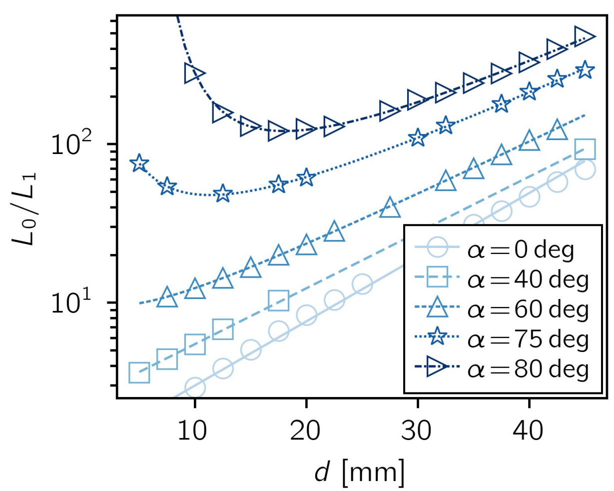
- Consistency of L_0 over notably large frequency range results from dependency of the TE11 cutoff frequency
- Large adjustment range of L_0 results from the nearly inverse dependency of the coupling factor between evanescent modes

$$L_0 \propto k^{-1} \text{ (coupling factor } k \propto \cos\alpha)$$

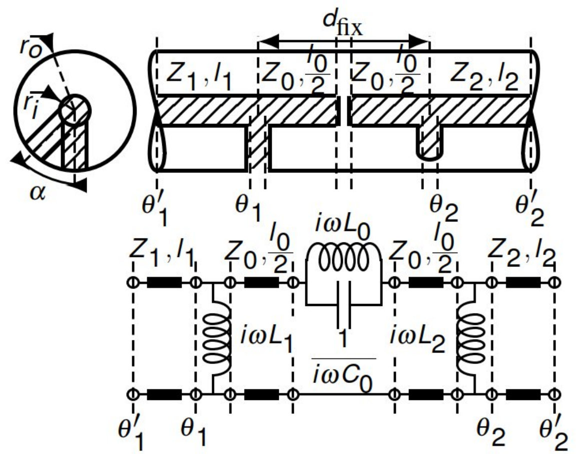
L0 Consistency and Cutoff dependency



Coupling factor dependency



microwave structure and equivalent circuit



Some thoughts on rudimentary approaches

FILTER DESIGN

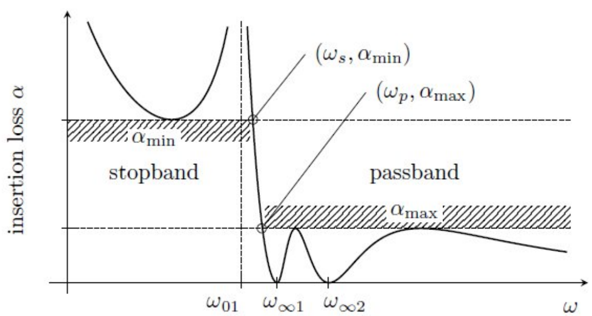
Filter design

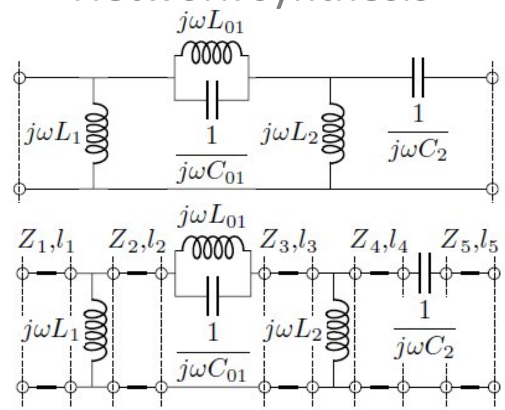
Synthesis based on fitting equivalent circuits

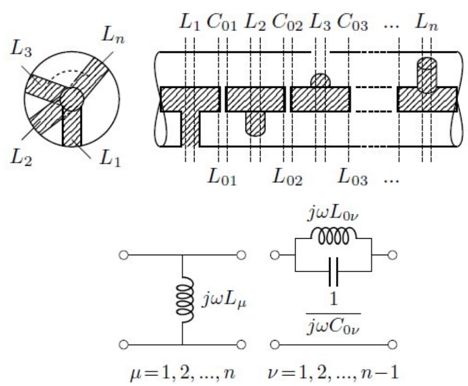
- If equivalent circuits exists, methods of network synthesis can be applied, particularly by means of ladder networks

Approximation problem | Network synthesis | Model fitting

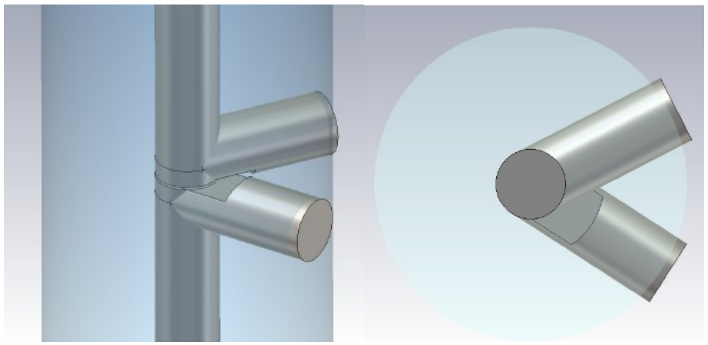
$$D(s) = c_1 \frac{(s^2+\omega_{\infty 1}^2)(s^2+\omega_{\infty 2}^2)}{s^2(s^2+\omega_{01}^2)}$$

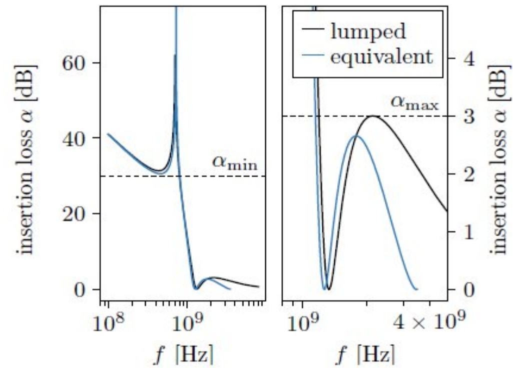






- Example of a third-order elliptic high-pass filter (704 MHz SPL)

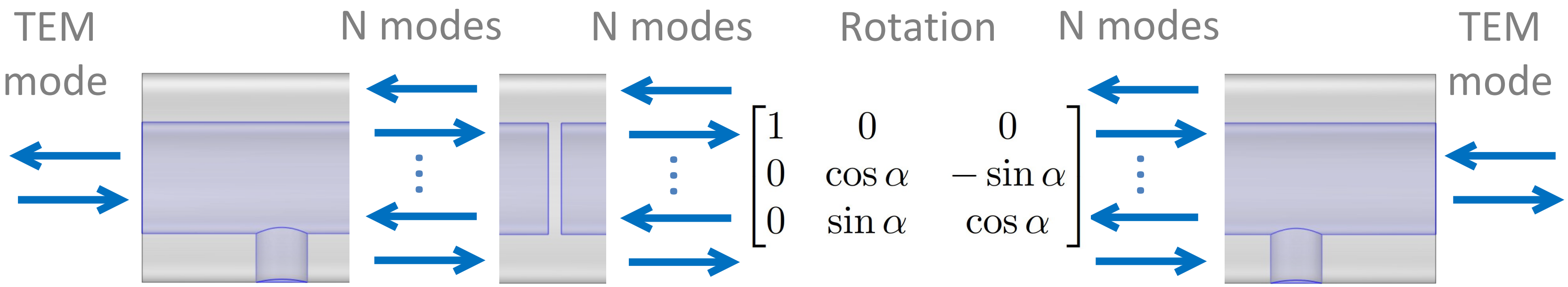




Filter design

Synthesis based on concatenation of scattering matrices

- Numerical optimization of parameterized segments using CSC



$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix}$$

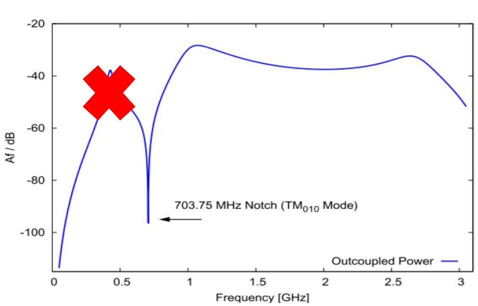
- Fully consistent to complete structure provided the necessary modes are involved
- 3D field simulations replaced by matrix multiplications and solving small linear matrix equations given **the minimal order representation** of the problem

CONCLUSION

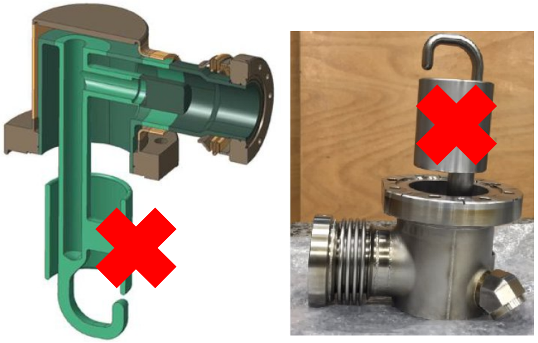
Conclusion

Evanescent mode coupling in coaxial HOM couplers allow for ...

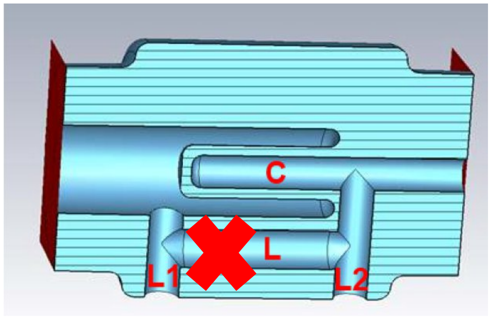
- Canonical topology -> Filter realization with minimal effort
- High-pass realization without parasitic effects below TE11 cutoff
- No need of large notch filter capacitance or series LC resonator
- Remarkable larger adjustment range of filter functions (equivalent circuit elements) in comparison to existing coupler designs
- In general compact design due to evanescent character
- Independent treatment of beam pipe/ cavity coupling and notch
- Broad band character -> matching focus: beam pipe/ cavity coupling
- Dismountable coupler designs
- Systematic design in principle without 3D numerical simulations



W. Xu, et. al., in Proc. PAC 2011 , TUP060



B. P. Xiao, et al. DQW-CC HOM Coupler,



B. P. Xiao, et al., in Proc. SRF2013

Outlook

Still a lot of work to do ...

- Equivalent circuits including quadrupole modes and simplifications for filter synthesis
- Investigate the scalability of the filter order and limits in more detail
- Refine and automatize design processes from filter function to microwave structure
- Experimental studies and application in real facilities

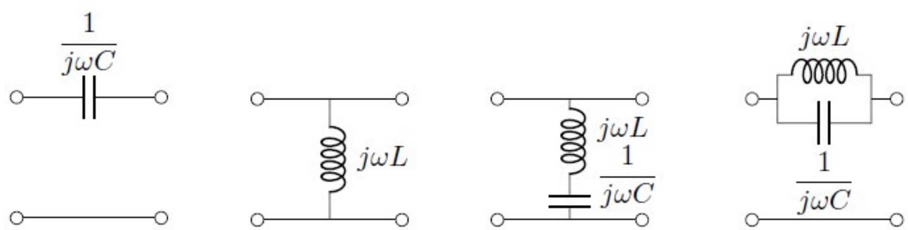
Thank you very much

EXTRA SLIDES

Introduction

RF Filter Components, Equivalent Circuits, and Topology

- Analysis of numerous obstacles and discontinuities by model fitting
- Focus on elements that are appropriate for high-pass filters, i.e. equivalent behavior of

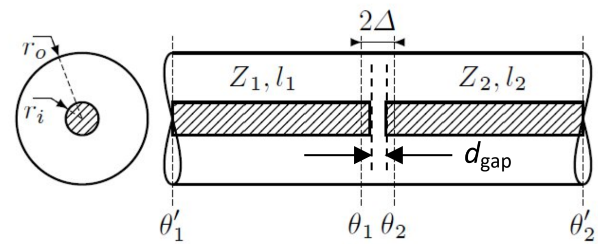


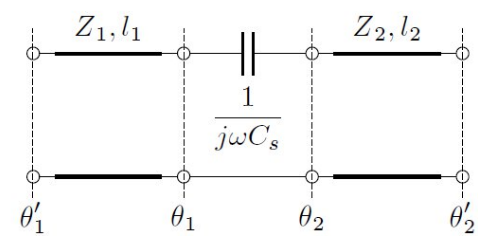
- Ex: Capacitive gap in coaxial guide
  - analytical or empirical approximation:

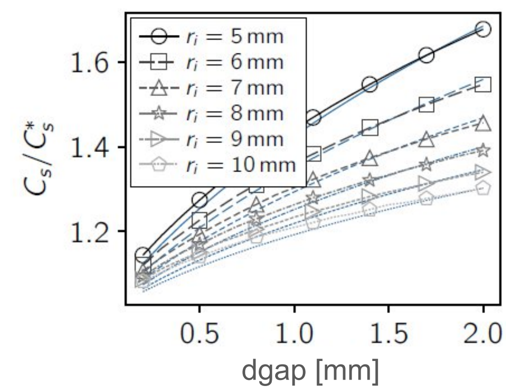
$$C_s = C_s^* + 1.965\varepsilon_0 r_i \ln 2 \frac{r_o - r_i}{d_{\text{gap}}} \qquad C_s^* = \varepsilon_0 \frac{\pi r_i^2}{d_{\text{gap}}}$$

[Matthaei et. al, "Microwave Filters, Impedance-Matching Networks, and Coupling Structures"]

Coaxial line with capacitive gap



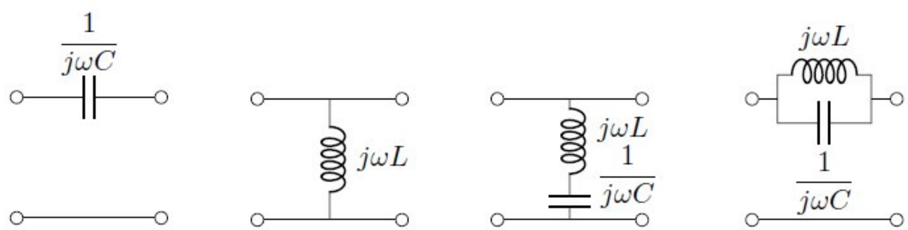




Introduction

Some thoughts on Filter theory and coaxial lines

- Analysis of numerous obstacles and discontinuities by model fitting
- Focus on elements that are appropriate for high-pass filters, i.e. equivalent behavior of

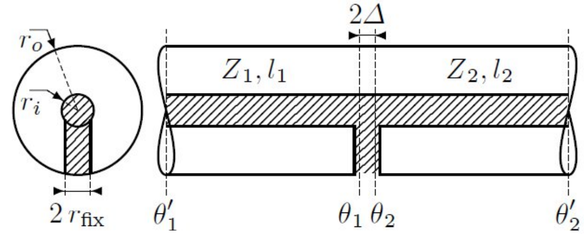


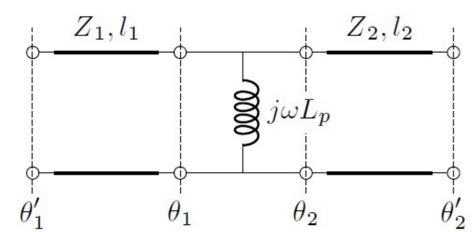
- Ex: Inductive post in coaxial guide
  - analytical or empirical approximation:

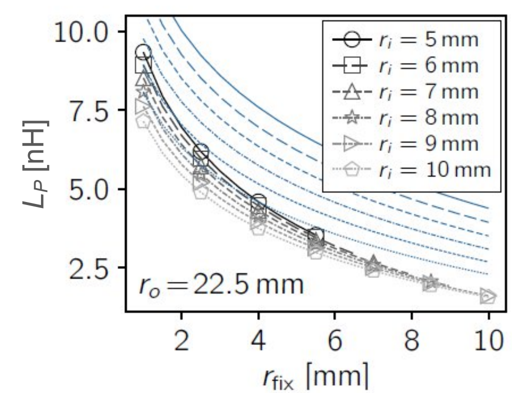
$$L_P = 0.367\mu_0(r_o - r_i)\log_{10} 2\frac{r_o - r_i}{r_{fix}}$$

[Matthaei et. al, "Microwave Filters, Impedance-Matching Networks, and Coupling Structures"]

Coaxial line with inductive post



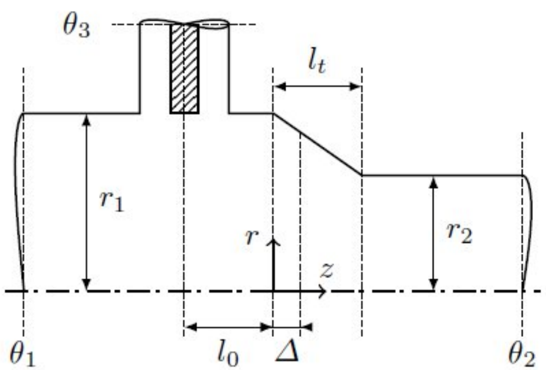




Coaxial Couplers and Synthesis

Transmission Zeros in Cutoff Tubes

- No coupling due to vanishing fields at coupler location (resonance in cutoff tube)



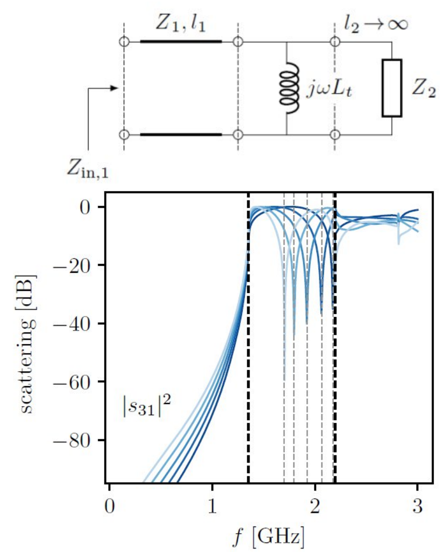
Probe antenna mounted on cutoff tube

- Independent of coupler design
- Influenced by waveguide, taper and coupler location
- Ensure distance from HOMs

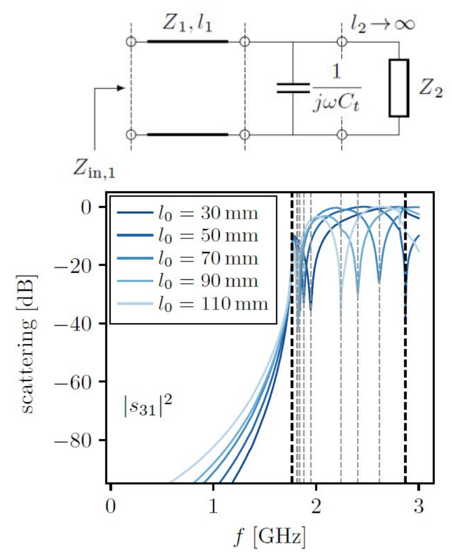
Transmission zeros of the high- SPL cutoff tubes

Cavity side	r_1 [mm]	r_2 [mm]	l_t [mm]	l_0 [mm]	f_1 [GHz]
Tuner	65	40	28	30	1.85-1.96
FMC	70	40	34	59	1.68-1.74

TEM-TE_{11} transmission



TEM-TM_{01} transmission



Coaxial Couplers and Synthesis

Summary and Conclusions

- Analysis of numerous obstacles and discontinuities by model fitting
  - understanding of individual components of HOM couplers
  - basis for topological choice, synthesis, and numerical optimizations
  - equivalent behavior of capacitive gap between two inductive posts as a mid-shunt ladder possibly not documented so far
- First approach for the synthesis of transfer functions by means of coaxial microwave structures
  - still rudimentary but the principle has been proven
- Understanding of transmission zeros in cutoff tubes
  - transmission zeros of SPL cutoff tubes not harmful

Coaxial Couplers and Synthesis

Equivalent Circuit Parameter Characterization of RF Filter Components

- Example coaxial guide with capacitive gap between two inductive posts

freq. domain simulation $\mathbf{S}'(\omega_{\boldsymbol{k}})$

↓

phase shift $\mathbf{S} = \mathbf{w}\mathbf{S}'\mathbf{w}$

↓

2-port parameter transformation $\mathbf{S}(\omega_{\boldsymbol{k}}) \rightarrow \mathbf{T}(\omega_{\boldsymbol{k}})$

→

$\mathbf{T}_{\text{model}}(\omega)$

$$t_{11} = \frac{t_{12}}{\mathrm{i}\omega L_2} + \cos\beta l_0 - \frac{1}{2Z_0C_0}\frac{\omega}{\omega_0^2-\omega^2}\sin\beta l_0,$$

$$t_{12} = \mathrm{i}\frac{1}{C_0}\frac{\omega}{\omega_0^2-\omega^2}\cos^2\frac{\beta l_0}{2} + \mathrm{i}Z_0\sin\beta l_0,$$

$$t_{22} = \frac{t_{12}}{\mathrm{i}\omega L_1} + \cos\beta l_0 - \frac{1}{2Z_0C_0}\frac{\omega}{\omega_0^2-\omega^2}\sin\beta l_0,$$

$$t_{11}t_{22} - t_{12}t_{21} = 1.$$

↓

non-linear least square problem

$$\min_{\Delta_1,L_1,\Delta_2,L_2,Z_0,C_0} \sum_k \left\|\mathbf{T}(\omega_k) - \mathbf{T}_{\text{model}}(\omega_k)\right\|^2$$

↓

$L_0, C_0, L_1, L_2, Z_0, \lambda_1, \lambda_2$