BASICS OF MICROWAVE NETWORK ANALYSIS OF OPTICAL CIRCUITS

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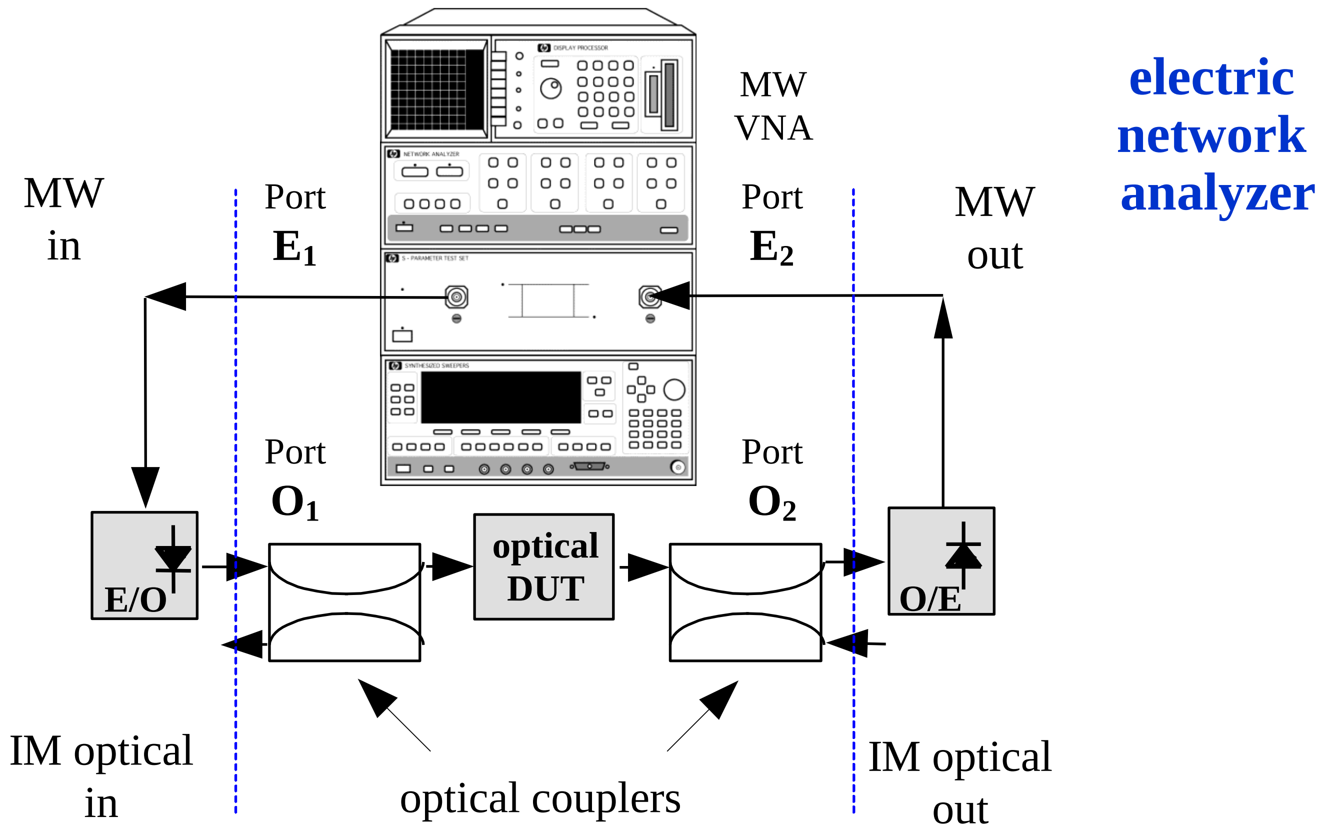
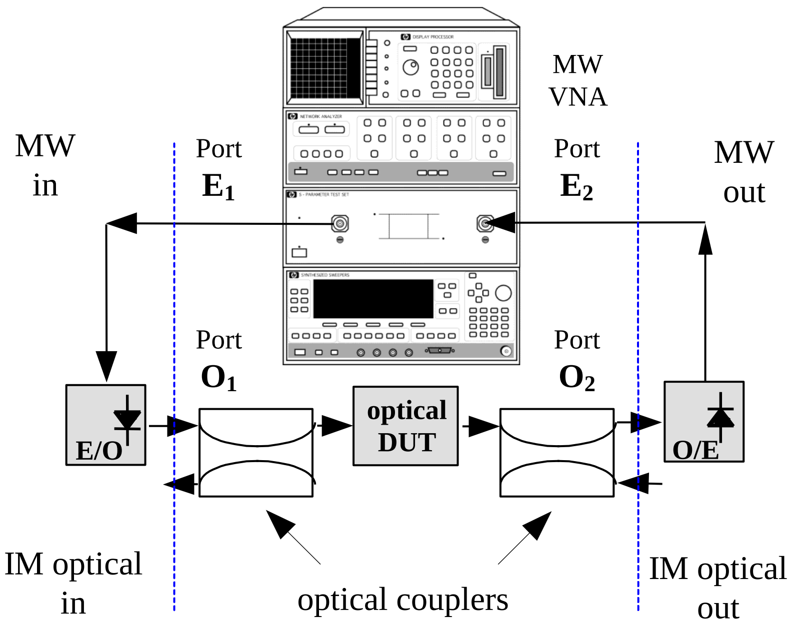
EXTENDING MICROWAVE NETWORK ANALYSIS INTO THE OPTICAL DOMAIN



- **E/O electro-optical converter (high-speed external modulator or laser diode)**
- **O/E opto-electronic converter (high-speed photodiode or photoreceiver)**

FOUR DIFFERENT MEASUREMENT POSSIBILITIES :

E/E, O/O, E/O, O/E



- **E/E between electrical ports E_1 and E_2 :**

  traditional MW network analysis, well-known error models and calibration procedures, wide literature

  [Hoefer, Eul, Schiek, Soares, Silvonen, Baranyi, Ladvánszky and others]

  MW network analysis of MW photonic systems including E/O converter(s) at the input(s) and O/E converter(s) at the output(s) of the optical subsystem

- **O/O between optical ports O_1 and O_2 :**

  microwave network analysis of purely optical circuits / systems

  often called as "all-optical MW circuits"

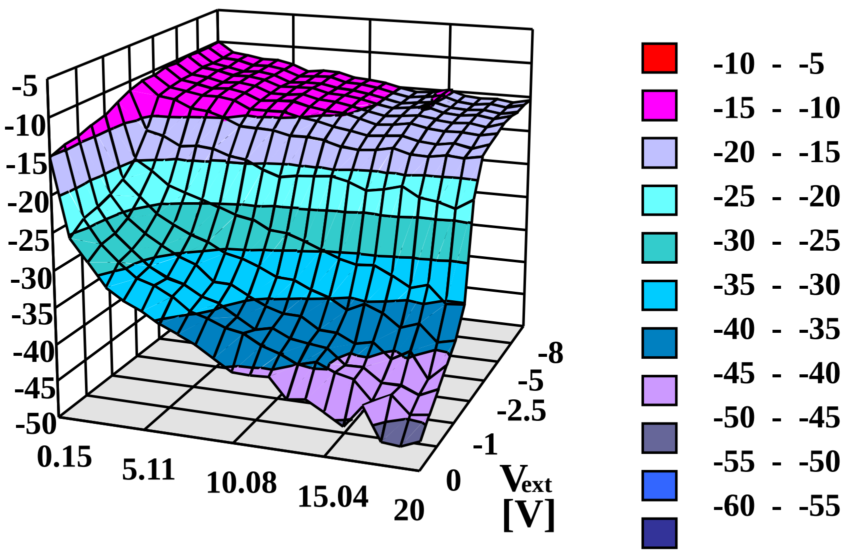
  existing error models, less known calibration procedure, some recent literature

  [Curtis et al, MTT 1990, Iezekiel et al., MWGL 1991, Ho-Quoc et al. EuMC 1994]

E/O or O/E Conversion Devices :

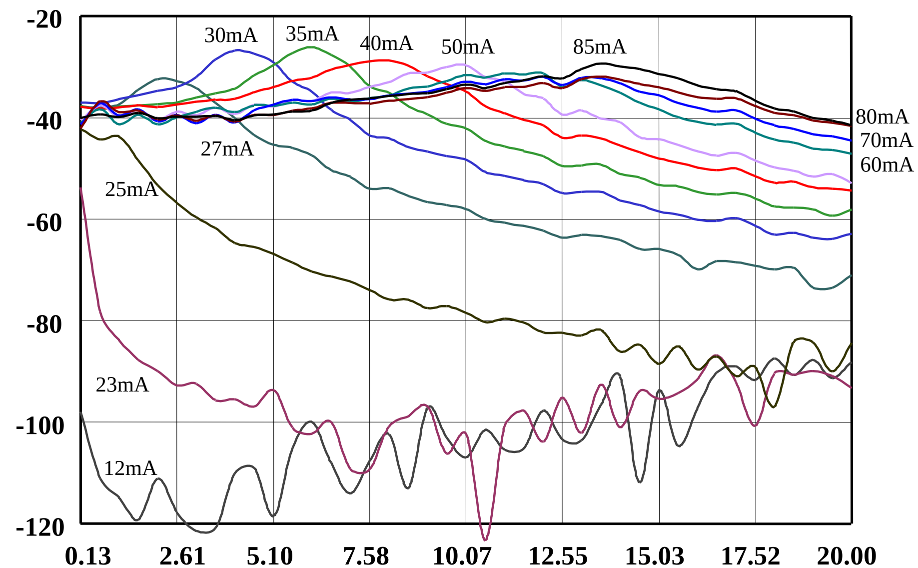
- **E/O between electrical input port E_1 and optical output port O_2 :**
  characterization of MW frequency response (bandwidth) of optical sources (LDs or optical modulators),
- **O/E between optical input port O_1 and electrical output port E_2 :**
  characterization of MW frequency response (bandwidth) of optical detectors (PDs or optical receivers),

O/E conversion : R_{PD} [dB(A/W)]



modulation frequency [GHz]

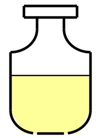
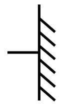
E/O conversion : R_{LD} [dB(W/A)]

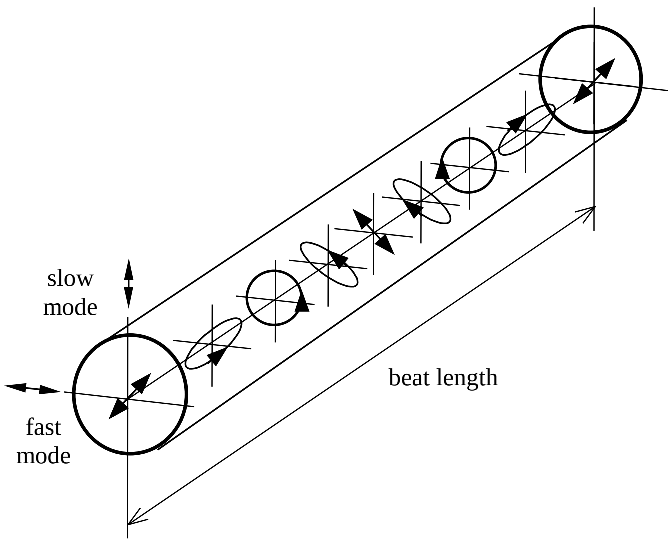


modulation frequency [GHz]

theoretically vector measurements are available, however in practice transmission measurements are limited to scalar tests (only electrical reflection tests are vectorial) due to difficult calibration problems, lack of calibration standards **[Debie and Martens, MTT 1995.]**

Basic Optical Circuits

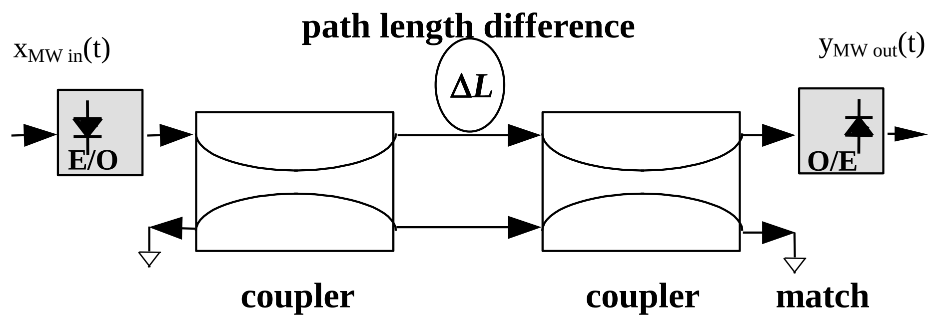
open load	open index matching oil	
short circuit	mirror	
coupler	coupler	



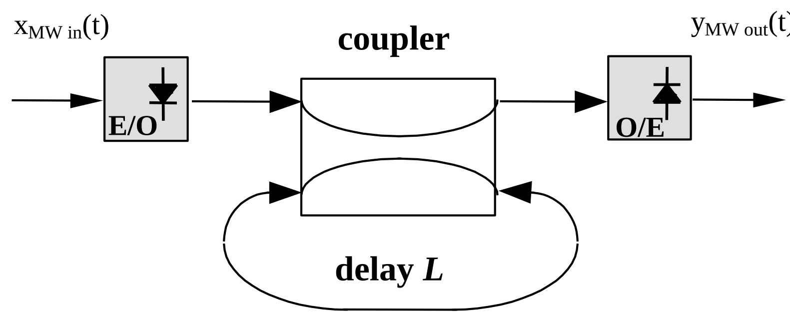
fiber (optical delay line)

most complicated component : birefrigence, dispersion, scattering, sensitivity to environmental stress (temperature, pressure), etc...

Unbalanced Mach-Zehnder Interferometer (UMZI)

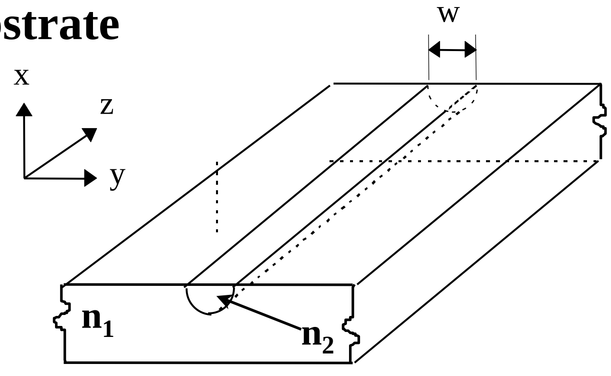


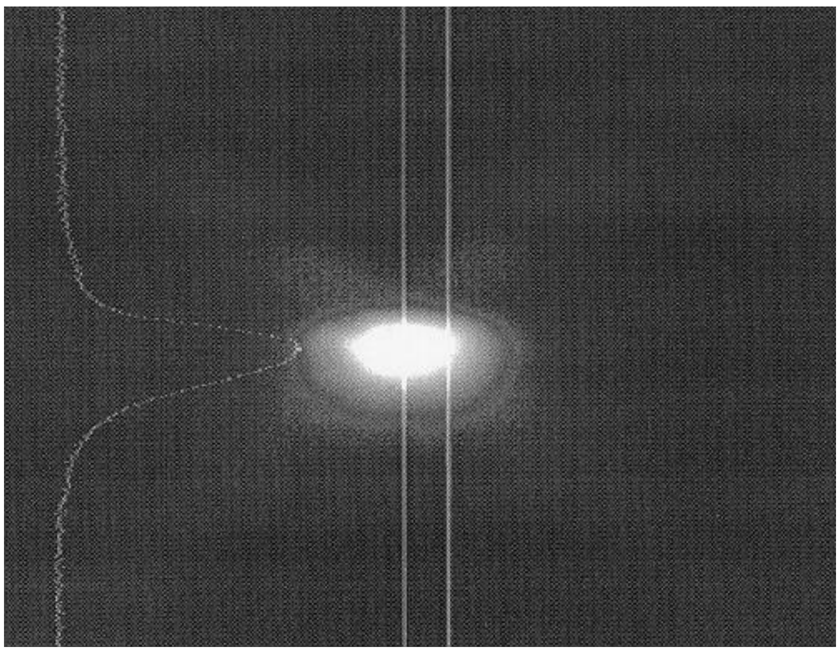
Recirculating Delay Line (RDL)

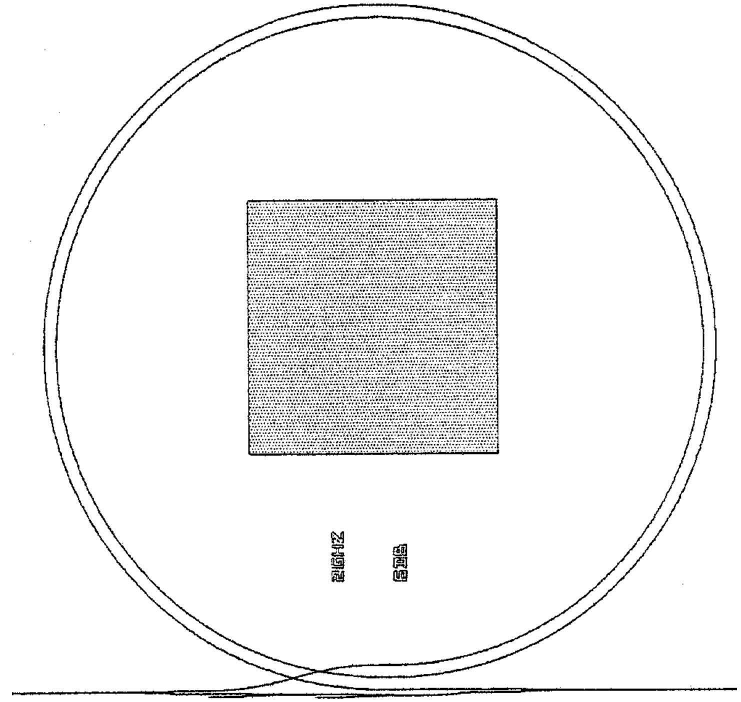


INTEGRATED OPTICAL DEVICES

straight optical waveguide on glass substrate







layout of an unbalanced Mach-Zehnder interferometer integrated on glass substrate

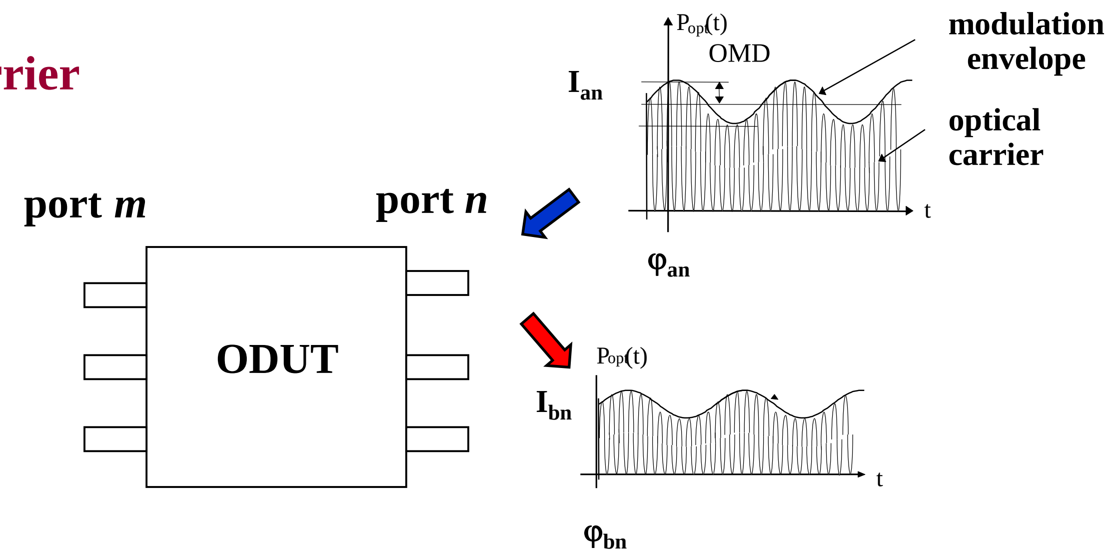
OPTOELECTRONIC *S*-PARAMETERS

transmission measurement of an all-optical circuit :

$$H_{ODUT}(\omega_{RF}) = \frac{H_{total}(\omega_{RF})}{H_{E/O}(\omega_{RF})H_{O/E}(\omega_{RF})}$$

by means of calibration the non-ideal response of E/O and O/E converters is removed.

IM envelope riding on an optical carrier



incident wave

$$a_n^o = I_{an} m \cos(\omega_{RF} t + \varphi_{an})$$

reflected wave

$$b_n^o = I_{bn} m \cos(\omega_{RF} t + \varphi_{bn})$$

reflection :

$$S_{nn}^o = \frac{b_n^o}{a_n^o} = \frac{I_{bn} m e^{j(\omega_{RF} t + \varphi_{bn})}}{I_{an} m e^{(j\omega_{RF} t + j\varphi_{an})}} =$$

$$\frac{I_{bn}}{I_{an}} e^{j(\varphi_{bn} - \varphi_{an})} = \left|\Gamma_{nn}^o\right| e^{j(\varphi_{bn} - \varphi_{an})}$$

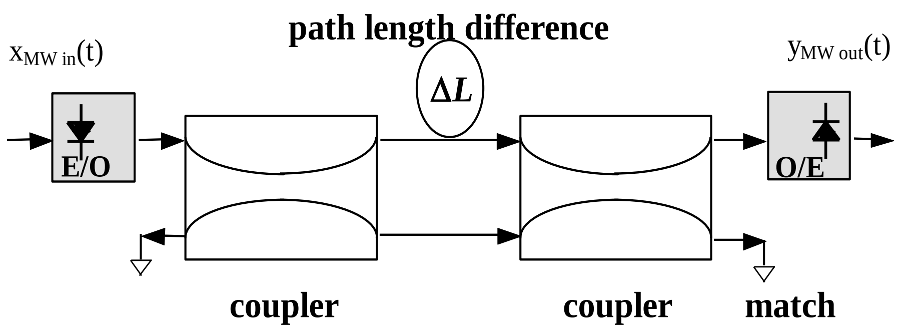
transmission :

$$S_{mn}^o = \frac{b_m^o}{a_n^o} = \frac{I_{bm}}{I_{an}} e^{j(\varphi_{bm} - \varphi_{an})}$$

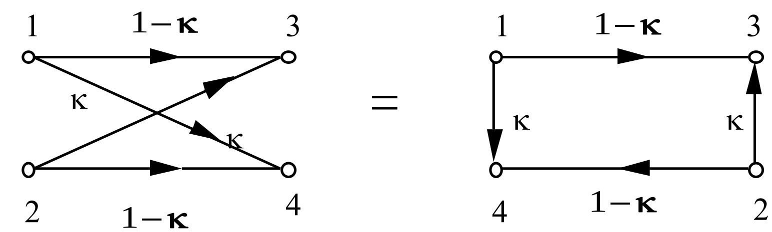
well-known rule of thumb : any loss in the optical part is doubled in the electrical domain

$$\left|S_{mn}^e\right| e^{j(\varphi_{bm}^e - \varphi_{an}^e)} = \left|S_{mn}^o\right|^2 e^{j(\varphi_{bm}^o - \varphi_{an}^o)} \quad \Rightarrow \quad \left|S_{mn}^e\right| [dBe] = 2\left|S_{mn}^o\right| [dBo]$$

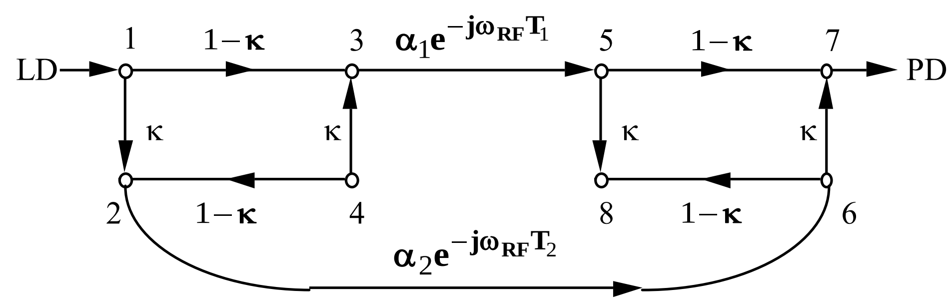
Microwave Frequency Response of the Unbalanced Mach-Zehnder Interferometer



equivalent graph of an ideal optical coupler :



graph representation of an UMZI :



delay $$\varphi_{RF} = \omega_{RF} T = \omega_{RF} \frac{L n_{eff}}{c}$$

delay difference $$\Delta T = \frac{L_2 - L_1}{c / n_{eff}} = \frac{\Delta L n_{eff}}{c}$$

3 dB optical couplers : κ=0.5 and lossless fiber delay lines : $\alpha_1 = \alpha_2 = 1$.

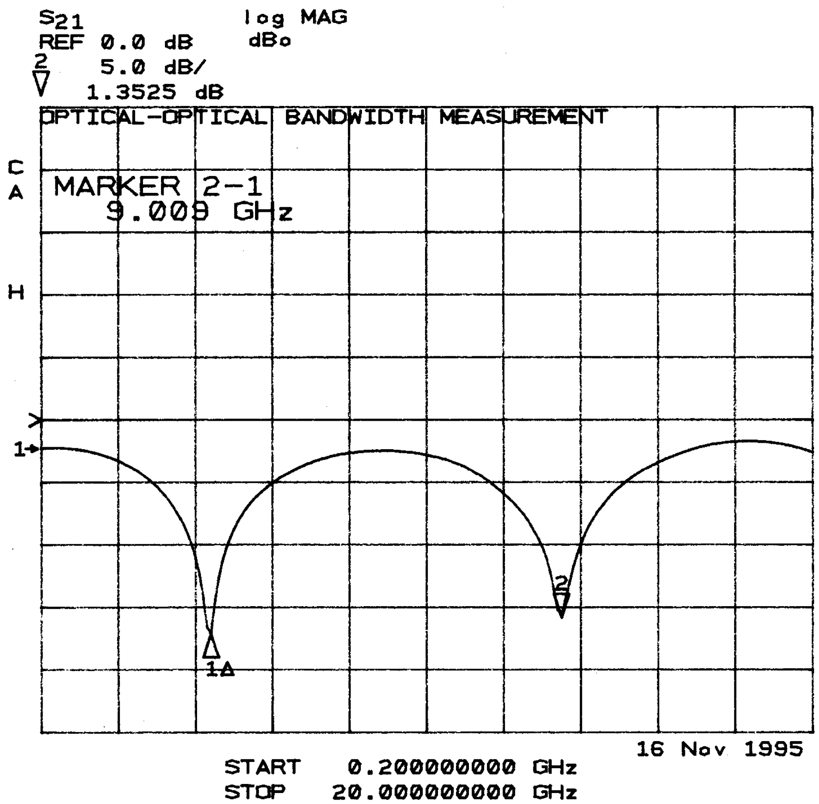
MicroWave Frequency Response :

$$H(\omega_{RF}) = \frac{1}{4} e^{-j\omega_{RF} L_1 n_{eff} / c} \left(1 + e^{-j\omega_{RF} \Delta L n_{eff} / c}\right)$$

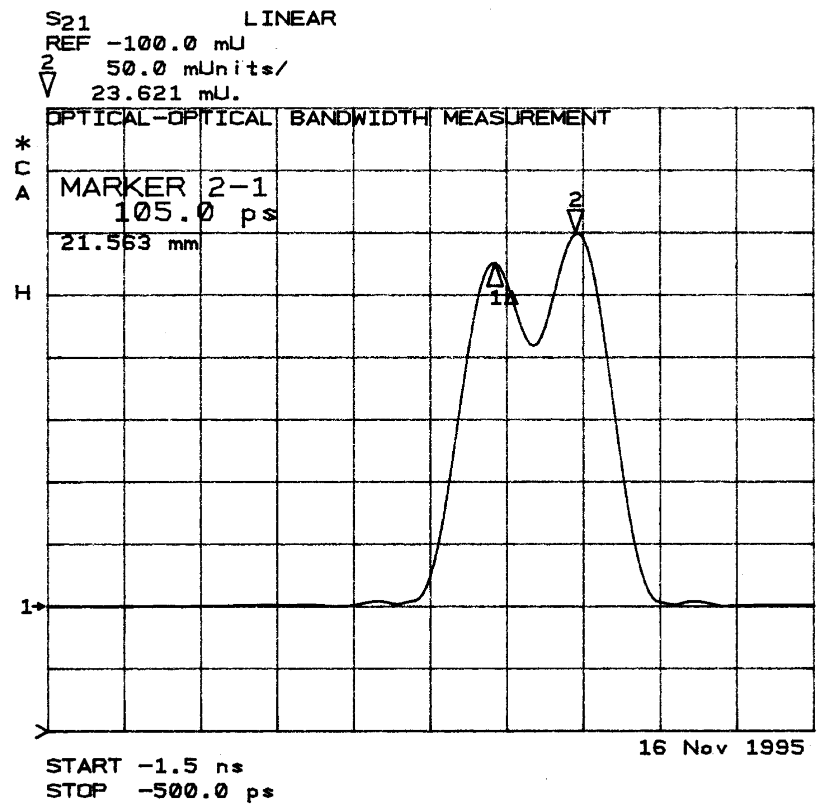
periodic rejections

MICROWAVE FREQUENCY RESPONSE

frequency domain

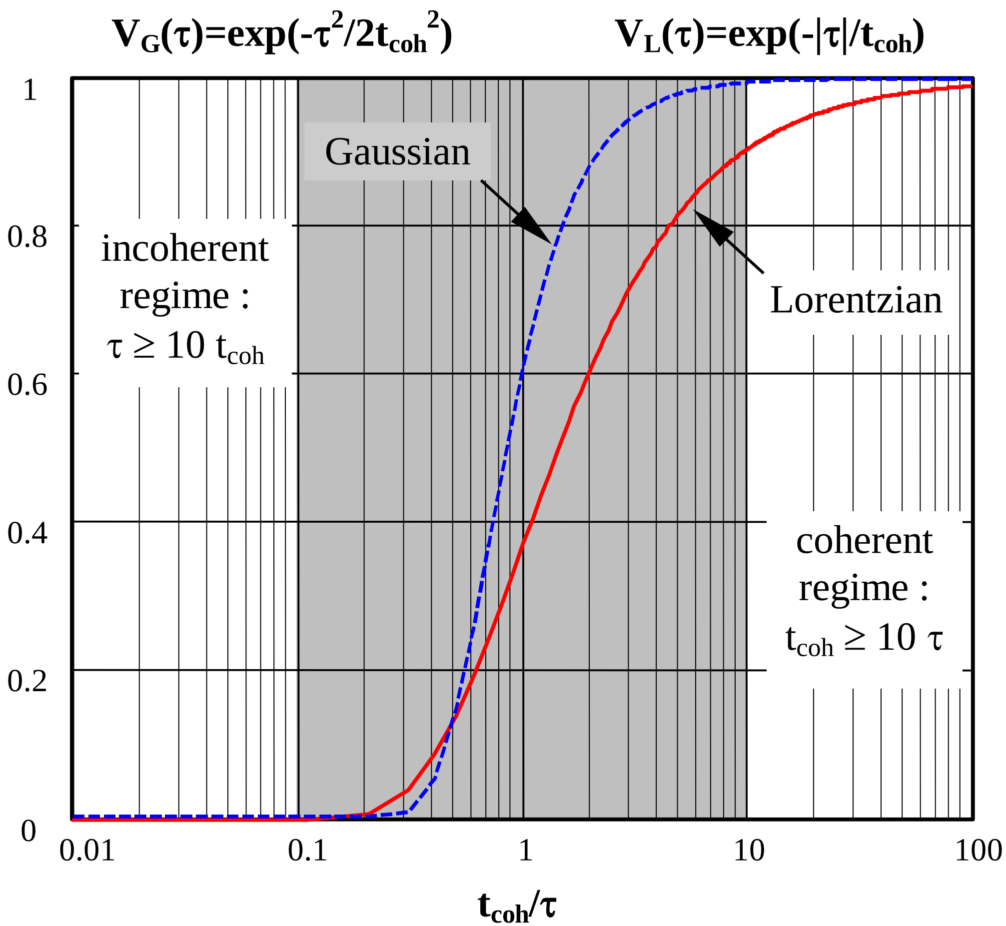


time domain



incoherent working regime → stable MW frequency response

EFFECT OF OPTICAL COHERENCE



Coherence length of the optical source might be comparable to the shortest path length difference within the optical circuit under test :

In coherent working regime the optical signals are added to each other in optical field not in intensity basis.

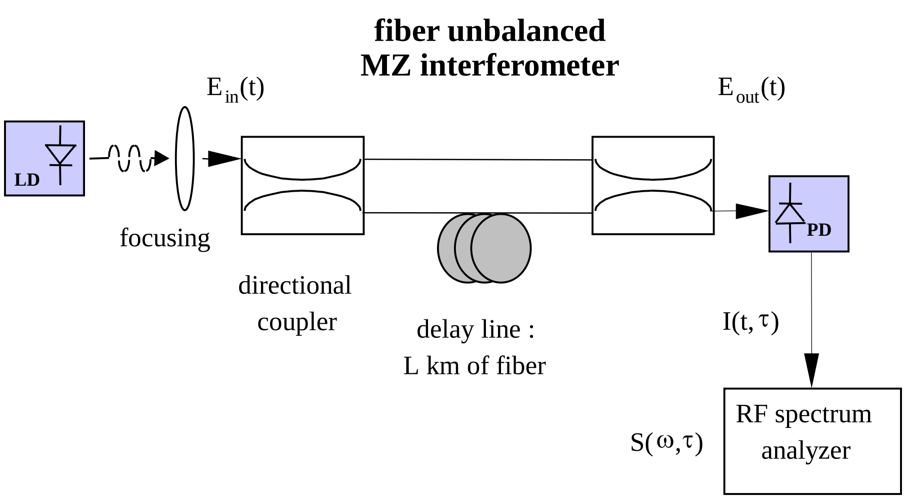
Models where intensity modulated optical signals arriving to the optical couplers are summarized simply on an intensity basis cannot explain the measured results !

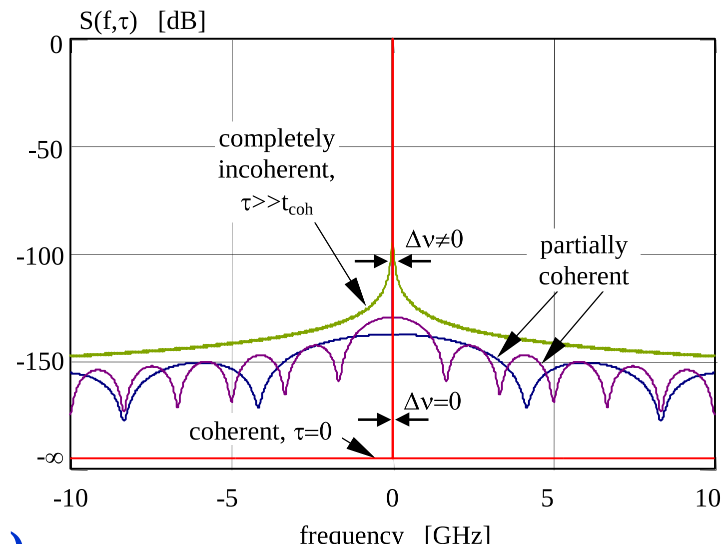
(Similar situation in MWP systems : incoherent models cannot explain chromatic dispersion effects in IM/DD links)

Coherence Length of Optical Sources in Fiber

Typical spectral / linewidth values of semiconductor optical sources

Optical source	spectral width	line-width	coherence length in fiber (n_{eff}=1.5)	Reference
light emitting diodes	22 - 4 THz		10 µm	[Senior, HP, Saleh, Weissman]
superluminescent diodes	4 THz		50 µm	[Weissman]
FP LDs	200 - 1 GHz		20 cm	[Senior, Weissman]
DFB LDs		100 - 10 MHz	2 - 20 m	[HP, Weissman, Krüger, Saleh, Agrawal]
DBR LDs		10 - 1 MHz	20 - 200 m	
external cavity LDs		300 kHz		[New Focus 6000 series lasers]
		50 kHz	4 km	[Weissman]
		6.4 kHz		[Tamir]

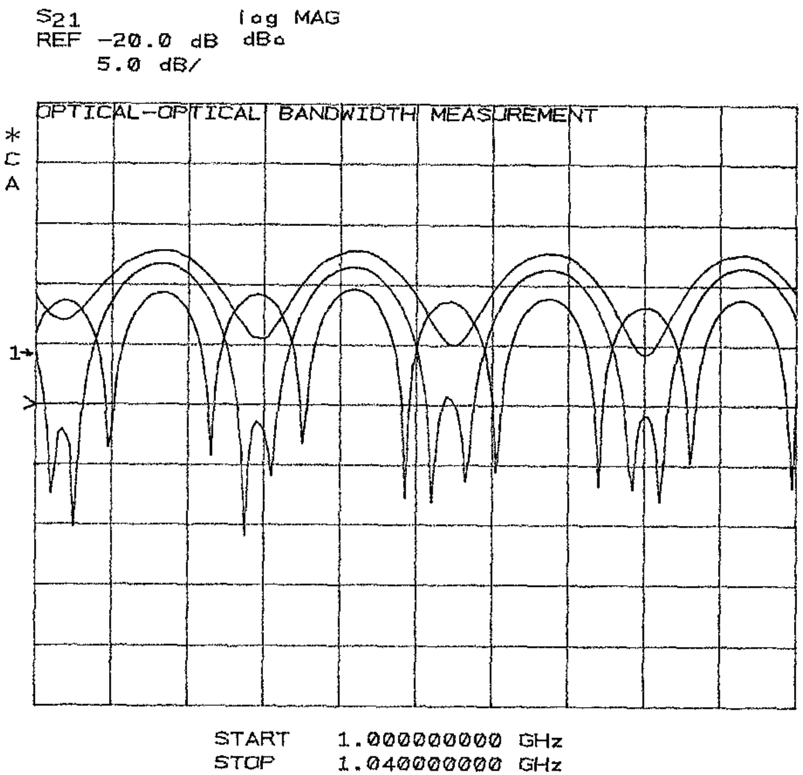




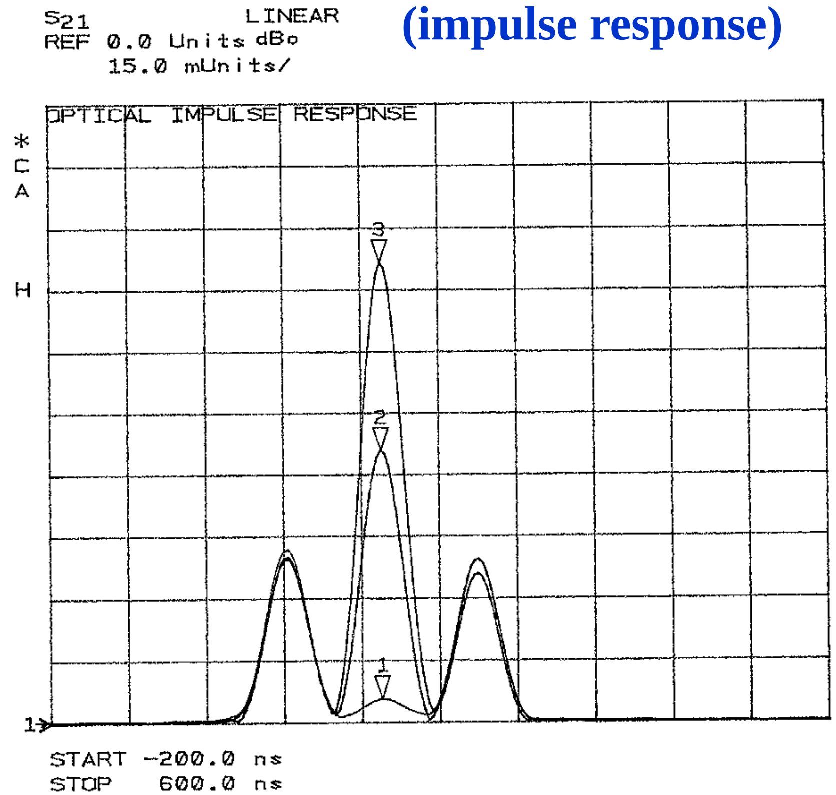
(MW source : >> 10 km)

MEASURED MWFR IN COHERENT WORKING REGIME

frequency domain



time domain,
(impulse response)



coherent working regime in optical domain

→ unstable frequency response in MW domain

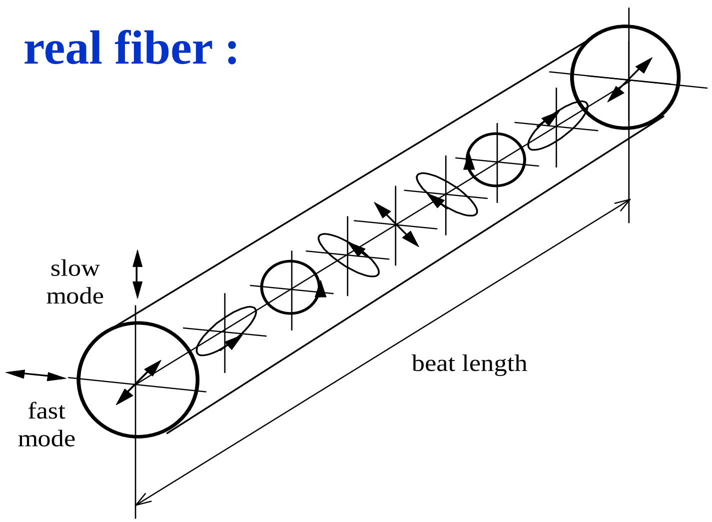
→ different MW frequency responses may be measured on the same optical circuit

→ optical carrier may disappear → only system noise of the VNA is measured

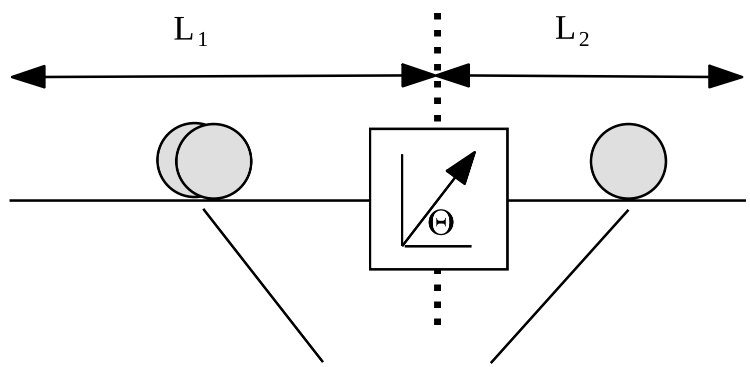
CASCADED STRUCTURES

often proposed for MW filtering in the optical domain **but stability of MW response ?**

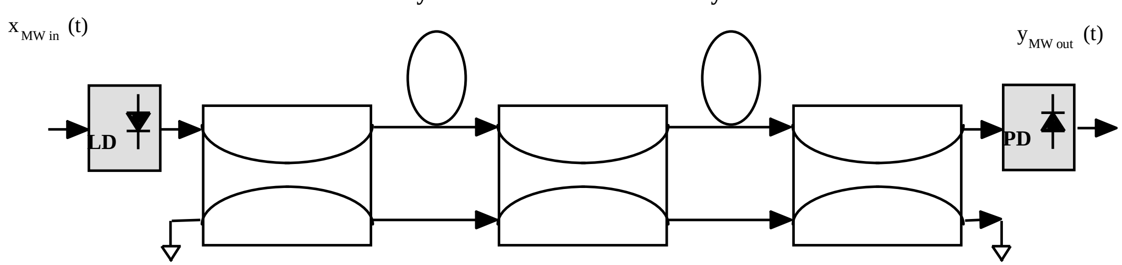
real fiber :

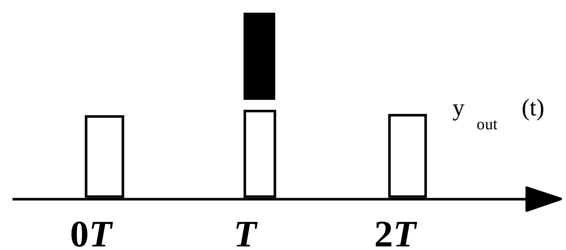


simple model :



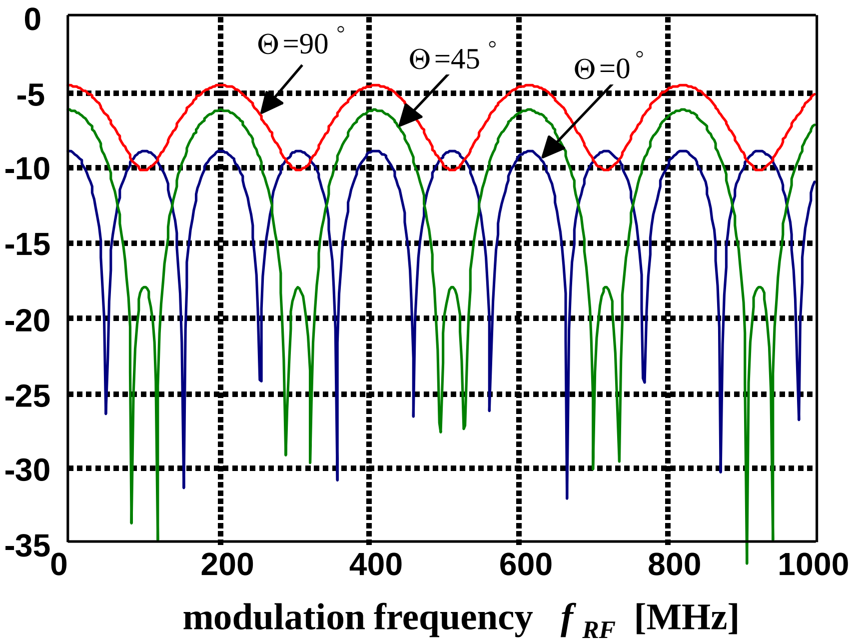
two-stage cascaded fiber UMZI :



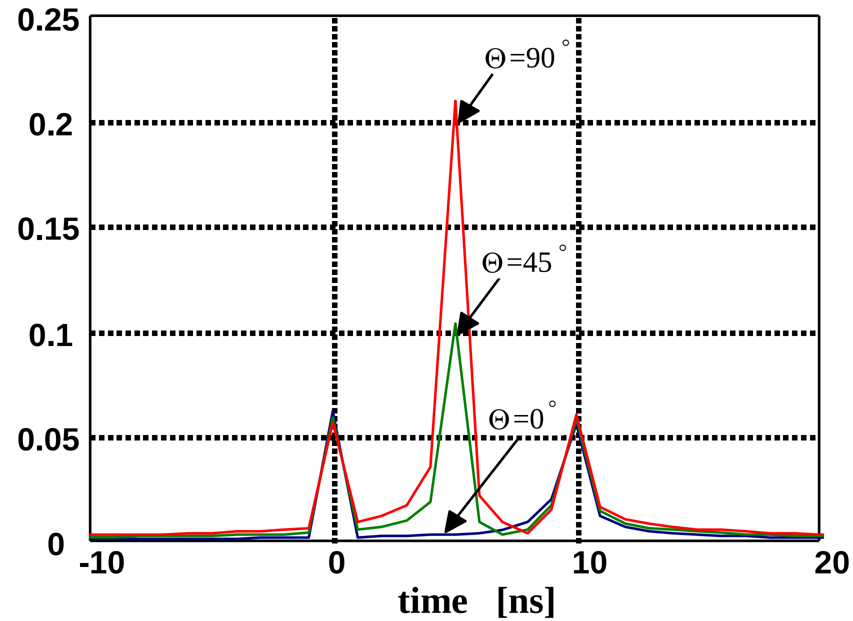


MwFr Simulated by Computer

MW frequency response [dBo]



Impulse response [aU]



Θ : polarization coupling, n_{eff}=1.46, $\Delta n=10^{-6}$,

m=0.2, $\kappa_x=\kappa_y=0.5$, L = 1 m, L_1 = 0.1 m, λ = 1.3 μm

second pulse → added up on field basis

$$\mathbf{I}_{t=T} = (\mathbf{E}_{2^{nd}\,path} + \mathbf{E}_{3^{rd}\,path})^2 \neq \mathbf{E}^2_{2^{nd}\,path} + \mathbf{E}^2_{3^{rd}\,path} = \mathbf{I}_{2^{nd}\,path} + \mathbf{I}_{3^{rd}\,path}$$

CONCLUSIONS :

- it is possible to extend microwave network analysis into the
  optical domain to characterize optical circuits/systems;

- four different measurement possibilities : E/E, O/O, E/O, O/E;

- basic optical circuits were shown : either fiber or integrated ;

- microwave frequency response of these basic optical circuits presented :
  measured results,
  simulated results;

- effects of
  optical coherence and
  polarization state of the optical carrier
  on the measured MW response is not negligible.

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UNOFFICIAL CONCLUSION :

“Basically we are still confused

but

hopefully on a higher level.”

(Jesper A. Jensen)

