IMS2012 MONTRÉAL
International Microwave Symposium
IEEE 17-22 June 2012, Montréal, Canada MTT-S
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Reconfigurable terahertz integrated architecture (RETINA) – a paradigm shift in SIW technology

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WFA: Integration and Technologies for mm-Wave Sub-systems

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Abstract

- Substrate integrated waveguide (SIW) technology has experience increased popularity in recent years, in the form of post-wall waveguides. However, the roots of this technology go back almost two decades with integrated dielectric-filled metal-pipe rectangular waveguides. One of the main drawbacks with SIW technology is the realisation of reconfigurable architectures at (sub-)millimetre-wave frequencies. To this end, a paradigm shift in the way components, circuits and front-end subsystems can be realised will be presented using the newly proposed REconfigurable Terahertz INtegrated Architecture (RETINA) technology. Here, 'virtual' side-walls within high resistivity silicon are created with a photo-induced 'metal-like' plasma, defined by light patterns than can be changed in real time. This new class of SIW technology allows individual components/circuits to be made tuneable and circuits/subsystems to be reconfigurable, simply by changing light source patterns. While still in its infancy, it is believed that for certain niche applications (e.g. where tuneability or reconfigurability is more important than Q-factor/loss performance) this technology could open up many new areas of (sub-)millimetre-wave research and development.

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Introduction

✍ At THz frequencies, guided-wave structures and resonators can in general exhibit:

• high integration and low cost – at the expense of high losses

• low loss – at the expense of poor integration and high cost

✍ At THz frequencies, reconfigurable & multifunctional front-end architectures represents a major challenge:

• prohibitively expensive

• impossible to integrate properly

Commercial 94 GHz metal-pipe rectangular waveguide systems architecture for medical research applications [http://www.aerowave.net/Custom.html]

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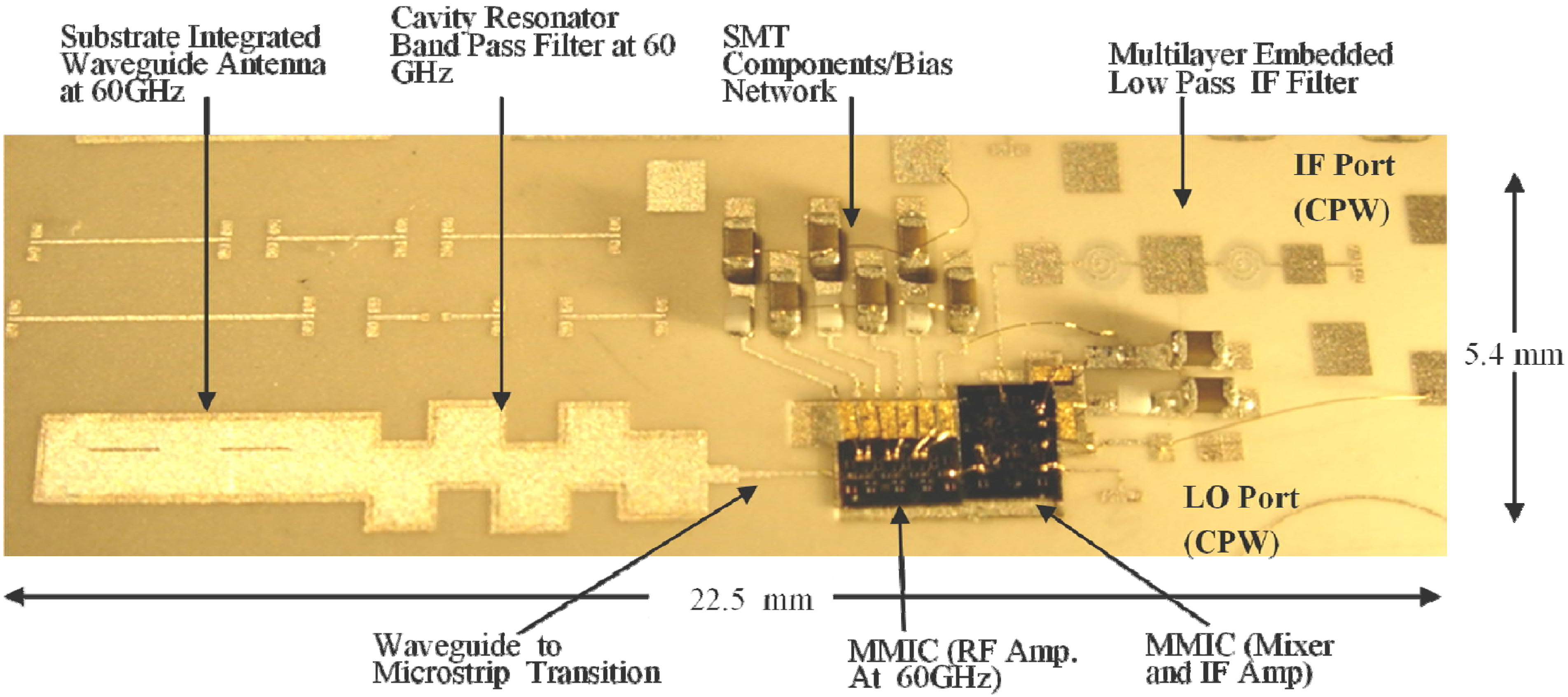
Complete 60 GHz system-on-substrate receiver



K. K. Samanta, D. Stephens and I. D. Robertson, "Design and performance of a 60-GHz multi-chip module receiver employing substrate integrated waveguides", *IET Microwaves, Antennas & Propagation*, vol. 1, no. 5, pp. 961-967, Oct. 2007.

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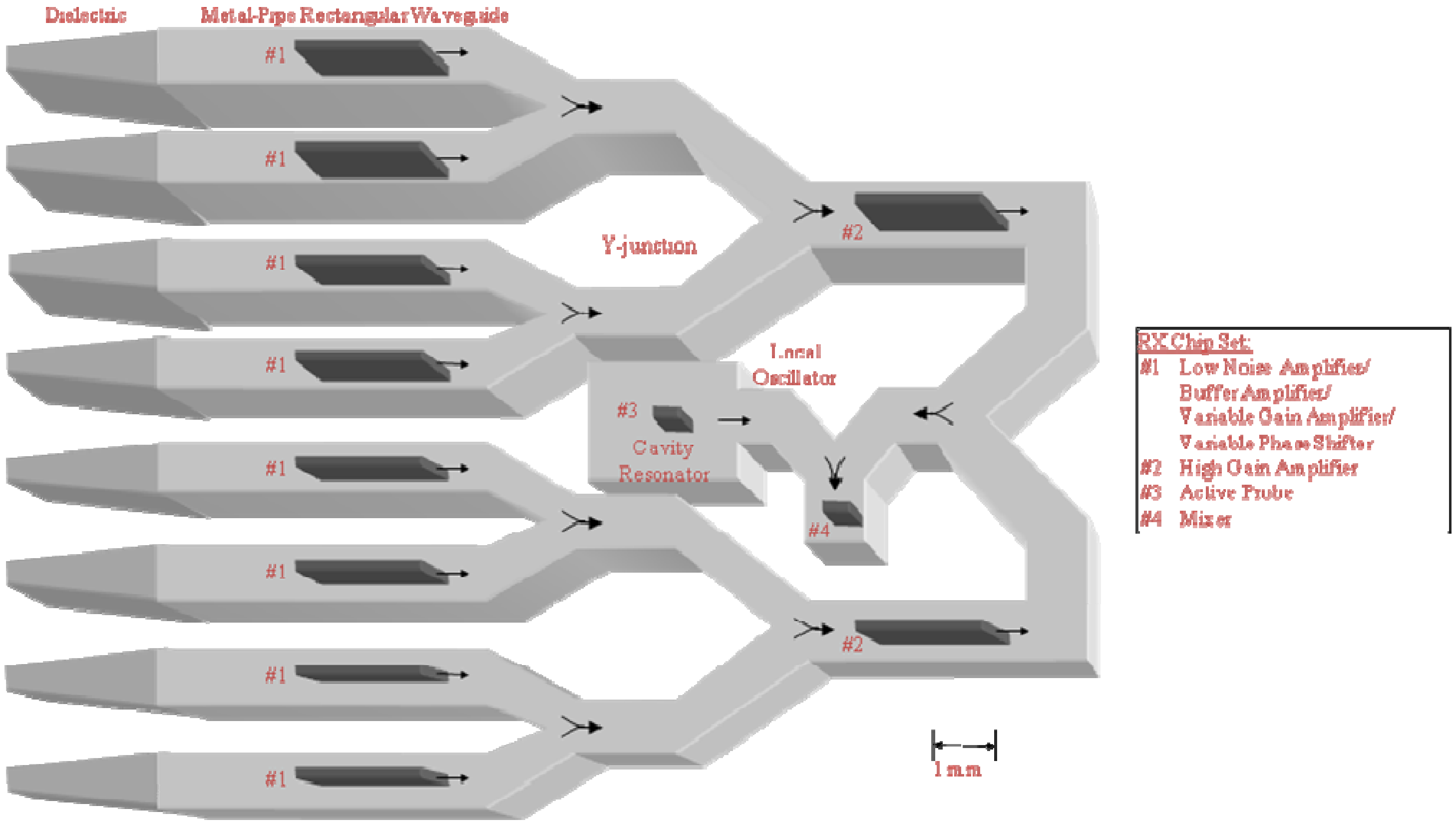
Illustration of a *'futuristic'* MCM receiver architecture concept, with integrated scanning phased array antenna



S. Lucyszyn, S. R. P. Silva, I. D. Robertson, R. J. Collier, A. K. Jastrzebski, I. G. Thayne and S. P. Beaumont, "Terahertz multi-chip module (T-MCM) technology for the 21st Century?", *IEE Colloquium Digest on Multi-Chip Modules and RFICs*, London, pp. 6/1-8, May 1998.

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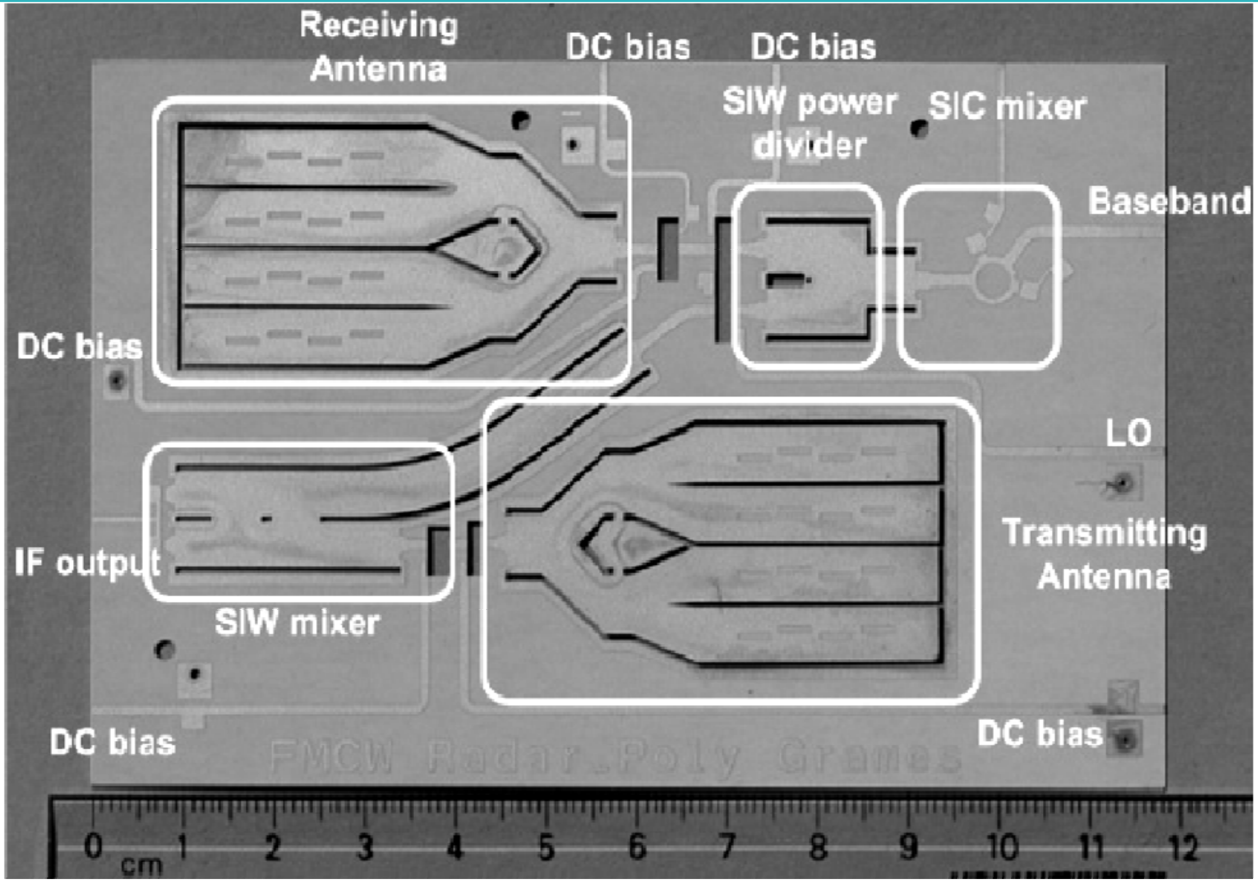
Complete 24 GHz FMCW radar front-end SoS, with integrated phased array antennas



Z. Li and K. Wu, "24-GHz frequency-modulation continuous-wave radar front-end system-on-substrate", *IEEE Transactions on Microwave Theory and Techniques*, vol. 45, no. 2, pp. 278-285, Feb. 2008.

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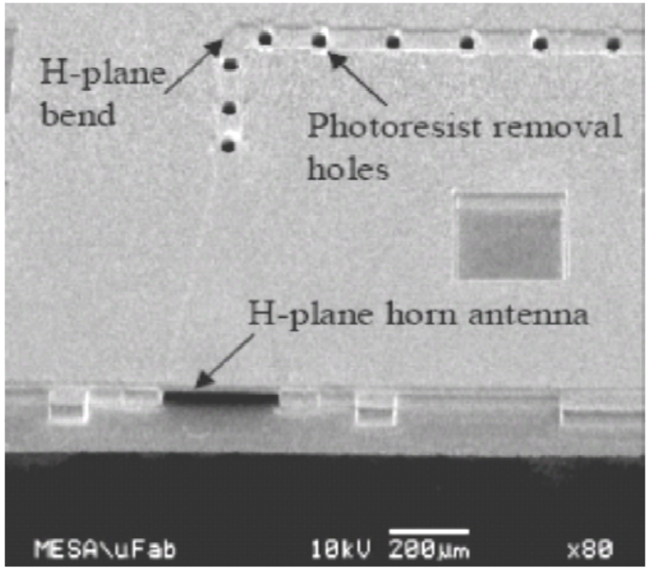
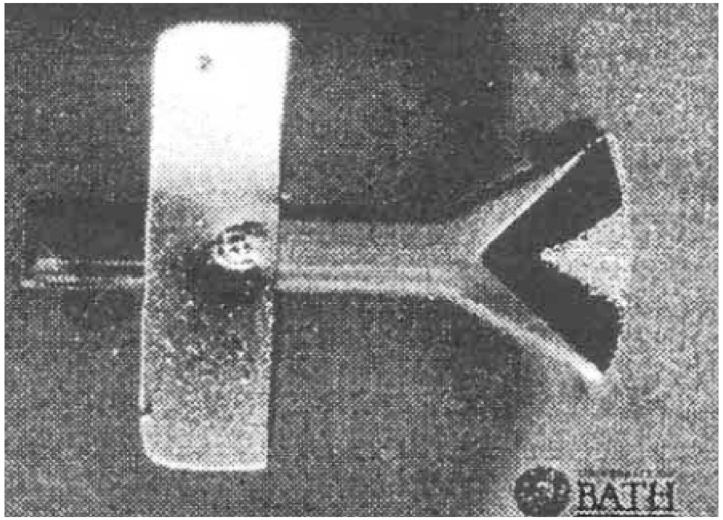
Examples of SoC technologies employing surface micromachining microfabrication processing



Part of a 3 THz metal-pipe rectangular waveguide array

C. D. Nordquist, M. C. Wanke, A. M. Rowen, C. L. Arrington, M. Lee, A. D. Grine, "Design, fabrication, and characterization of metal micromachined rectangular waveguides at 3 THz", *IEEE AP-S International Symposium*, pp. 1-4. Sep. 2008.

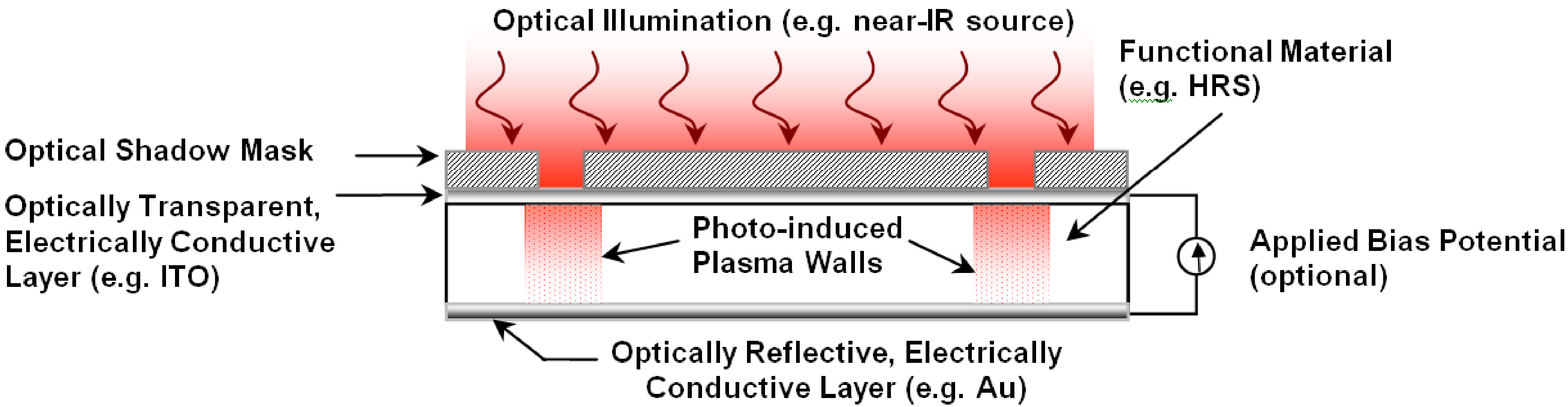


0.6 THz metal-pipe rectangular waveguide receiver

Kazemi, S. T. G. Wootton, N. J. Cronin, S. R. Davies, R. E. Miles, R. D. Pollard, J. M. Chamberlain, D. P. Steenson and J. W. Bowen, "Active micromachined integrated terahertz circuits", *Int. J. Infrared and Millimetre Waves,* vol. 20, no. 5, pp. 967-974, 1999.

RETINA Concept

- **Basic RETINA concept is based on creating virtual side walls**



S. Lucyszyn and Y. Zhou, "Reconfigurable Terahertz Integrated Architecture (RETINA)", *33rd Int. Conf. on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz 2008)*, Pasadena, USA, 2008.

Y. Zhou and **S. Lucyszyn**, "Modelling of reconfigurable terahertz integrated architecture (RETINA) SIW structures", *PIER J.*, vol. 105, 2010.

✍ Basic material parameters:

- Maximum photoconductivity – represents sidewall losses
- Dark conductivity – represents dielectric losses
- Carrier lifetime – defines the sidewall stability
- Band gap energy – dictates minimum illumination wavelength

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Typical properties of semiconductors at room temperature

Material	$\tau_L(s)$	E_g (eV)	μ (cm^{2}V^{-1}s^{-1})		σ_D (S/cm)	σ_m (S/cm)
			μ_n	μ_p		
HRS	10^{-6}–10^{-4}	1.1	1,500	600	10^{-6}–10^{-3}	$> 1,000$
Ge	10^{-4}	0.67	3,900	1,800	10^{-2}	> 600
GaAs	10^{-7}	1.43	8,500	400	10^{-2}	> 100
CdSe	10^{-4}	1.7	800	30	10^{-7}	2.77
InSb	10^{-7}	0.18	78,000	1,700	100	8,900
a-Si:H	–	0.7–0.8	1	0.02	10^{-9}–10^{-8}	10^{-3}–10^{-2}

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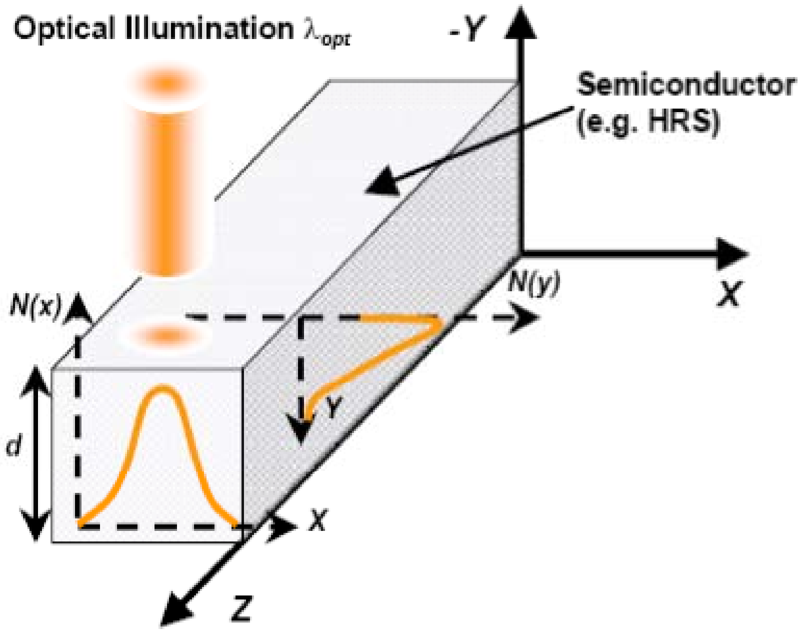
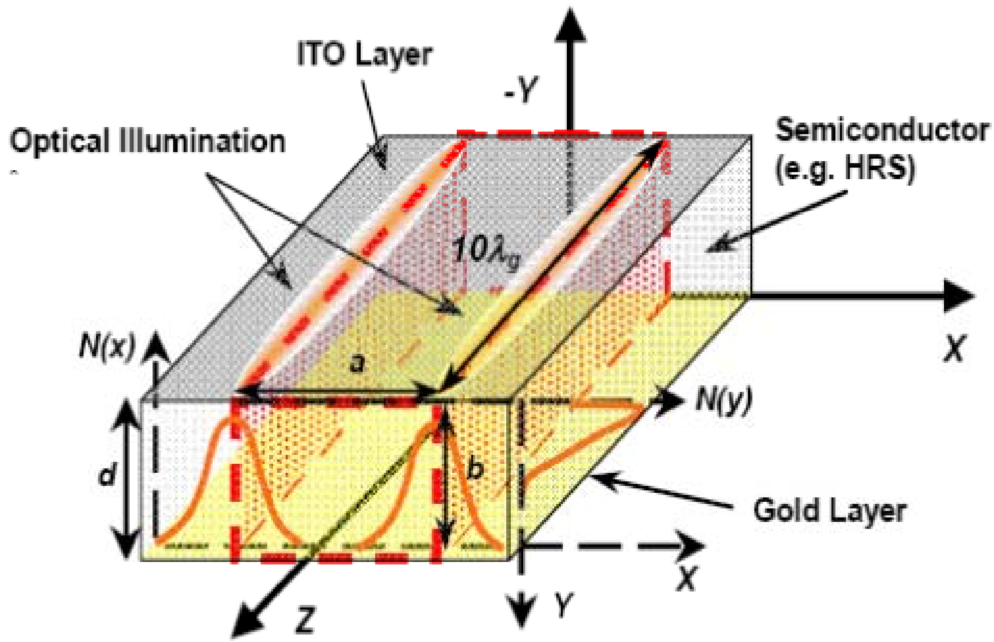
Carrier Density Modelling

Photoconductivity (PC) effect $\lambda_{opt}\,(\mu m) \le \dfrac{1.24}{E_g\,(eV)}$





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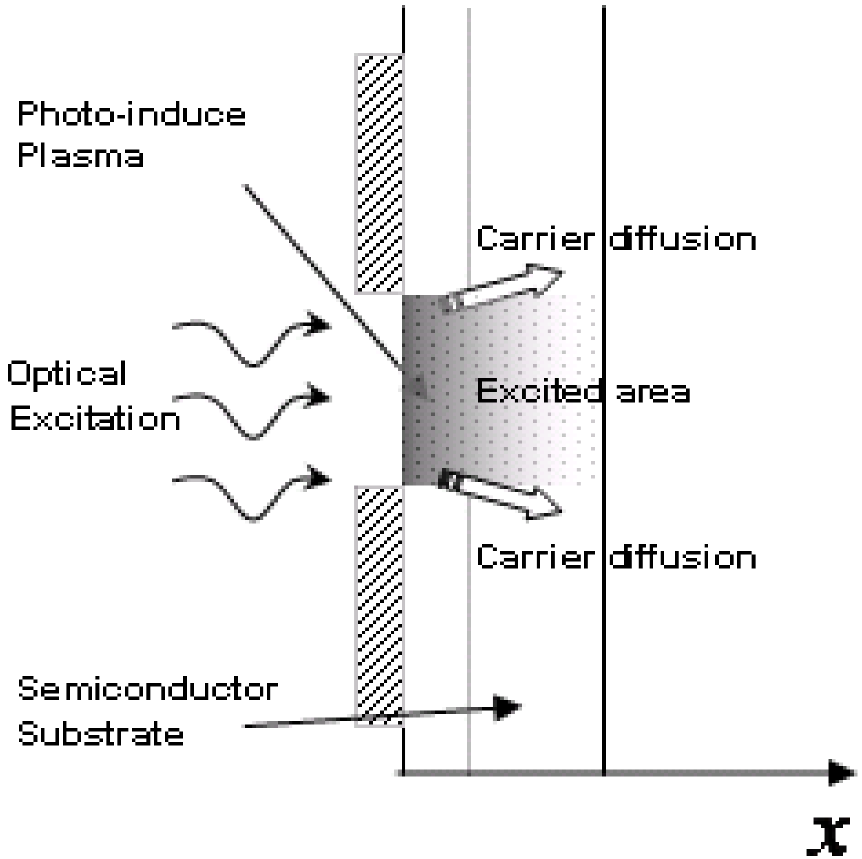
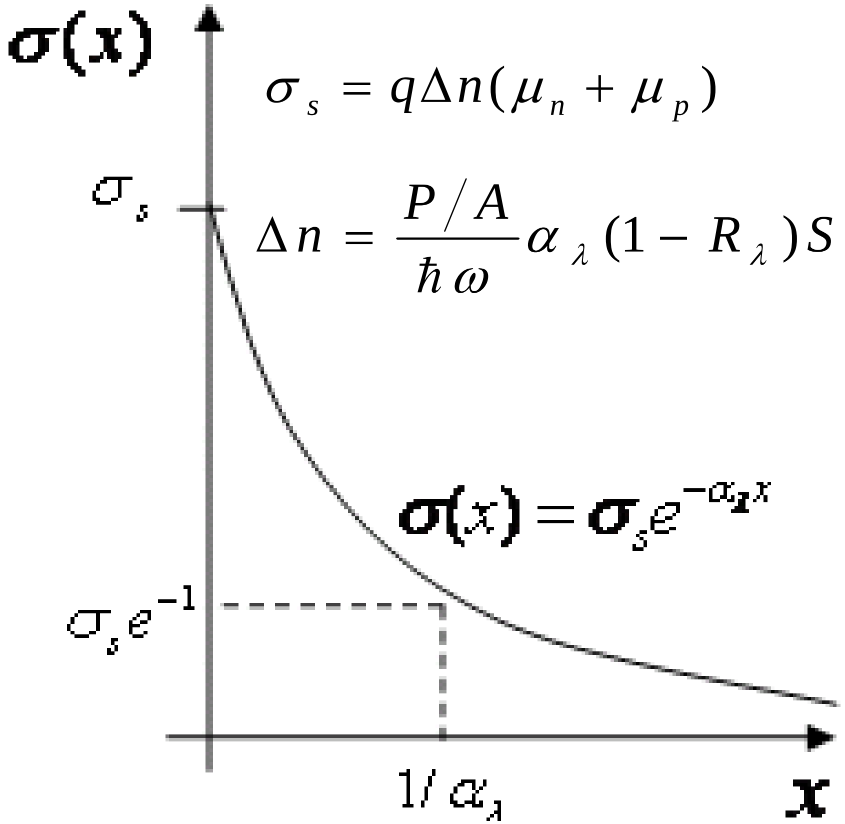
✍ Picosecond Pulse PC Effect

$$\sigma(x) = \sigma_s e^{-\alpha_\lambda x}$$



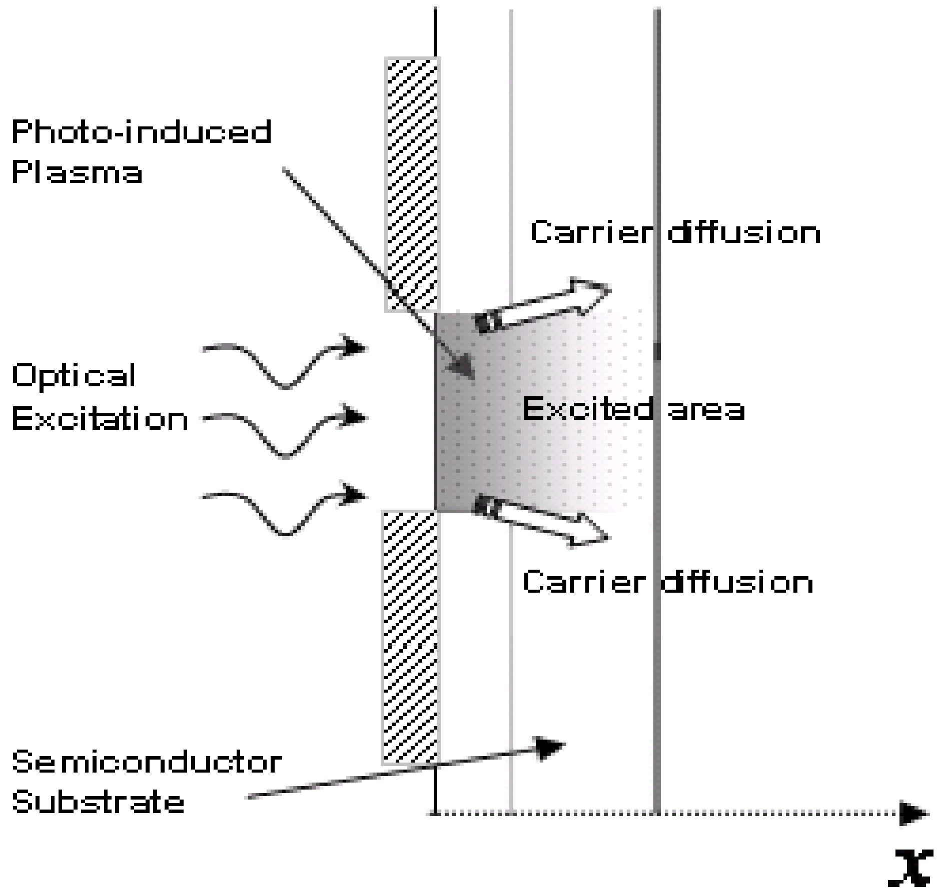
$$\sigma_s = q\Delta n(\mu_n + \mu_p)$$

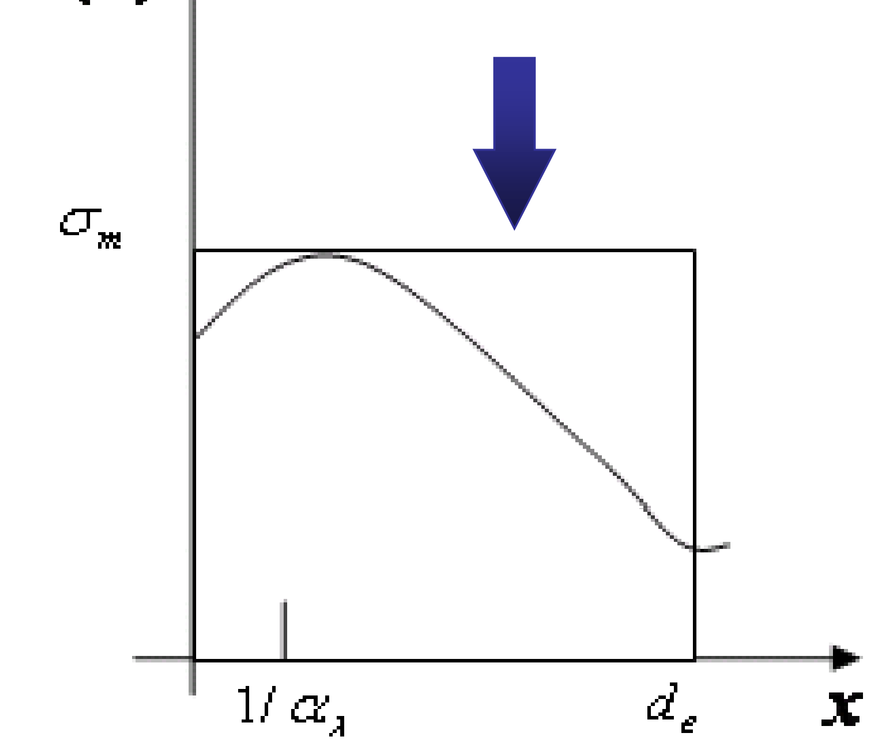
$$\Delta n = \frac{P/A}{\hbar\omega}\alpha_\lambda(1 - R_\lambda)S$$



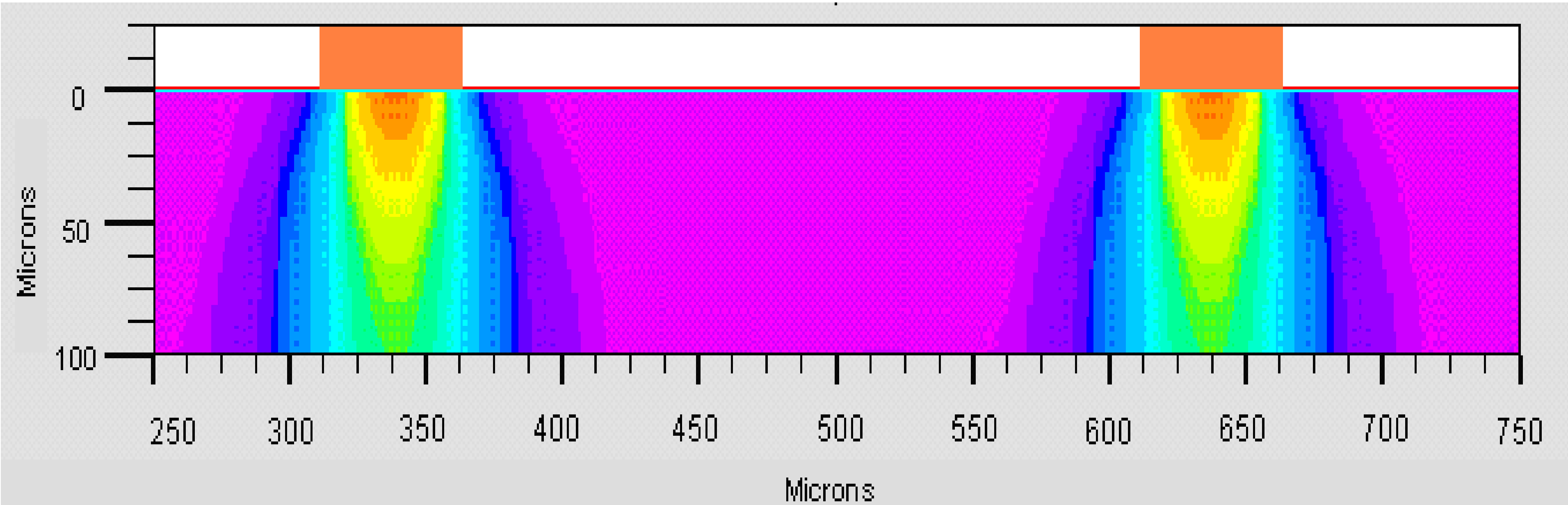
✍ Continuous Wave PC Effect

$$\sigma(x)=\frac{\sigma_0}{(1-\alpha_\lambda{}^2 L_a^2)}\times\left\{\exp(-\alpha_\lambda x)-\frac{\alpha_\lambda L_a^2+\nu_s\tau}{L_a+\nu_s\tau}\exp(-x/L_a)\right\}$$





✍ Silvaco™ TCAD simulations: 2D Luminous



Beam Width = 50 μm
Wafer Thickness = 100 μm
Optical Incident Power Range: 10-100 W/cm^2

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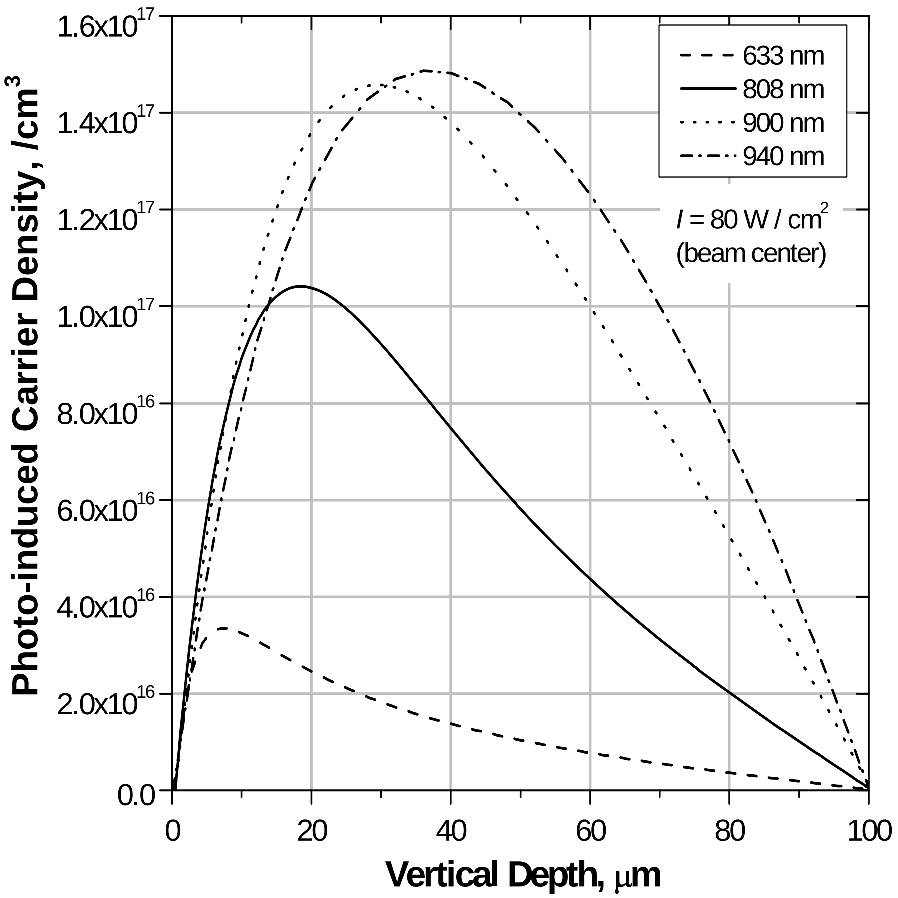

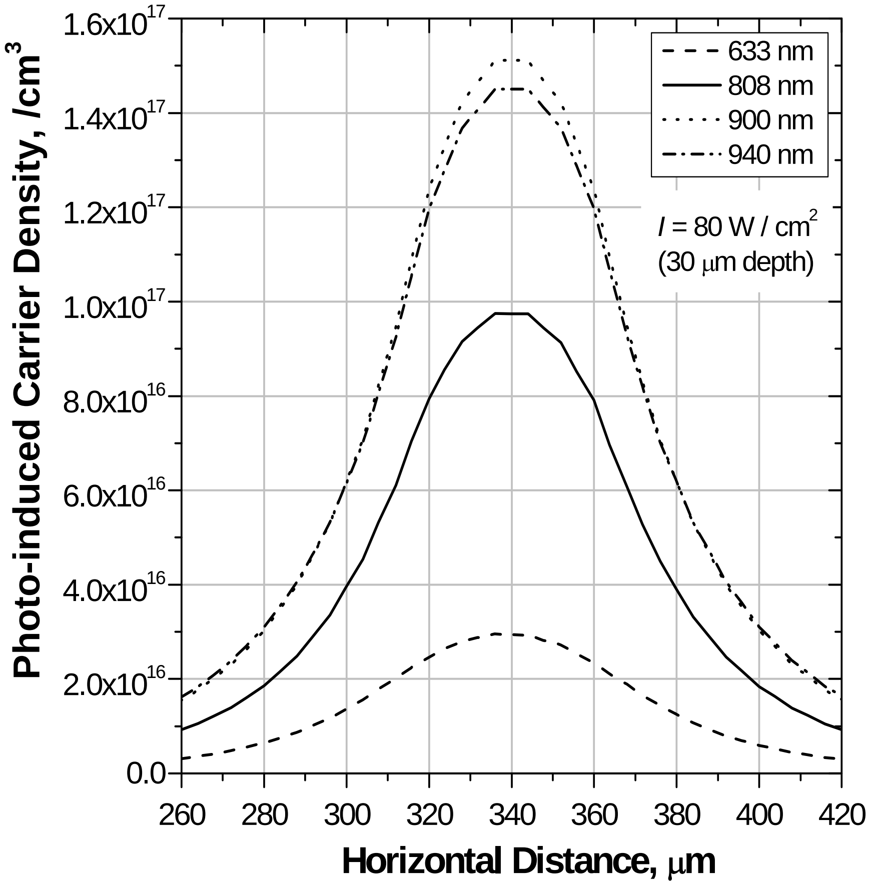

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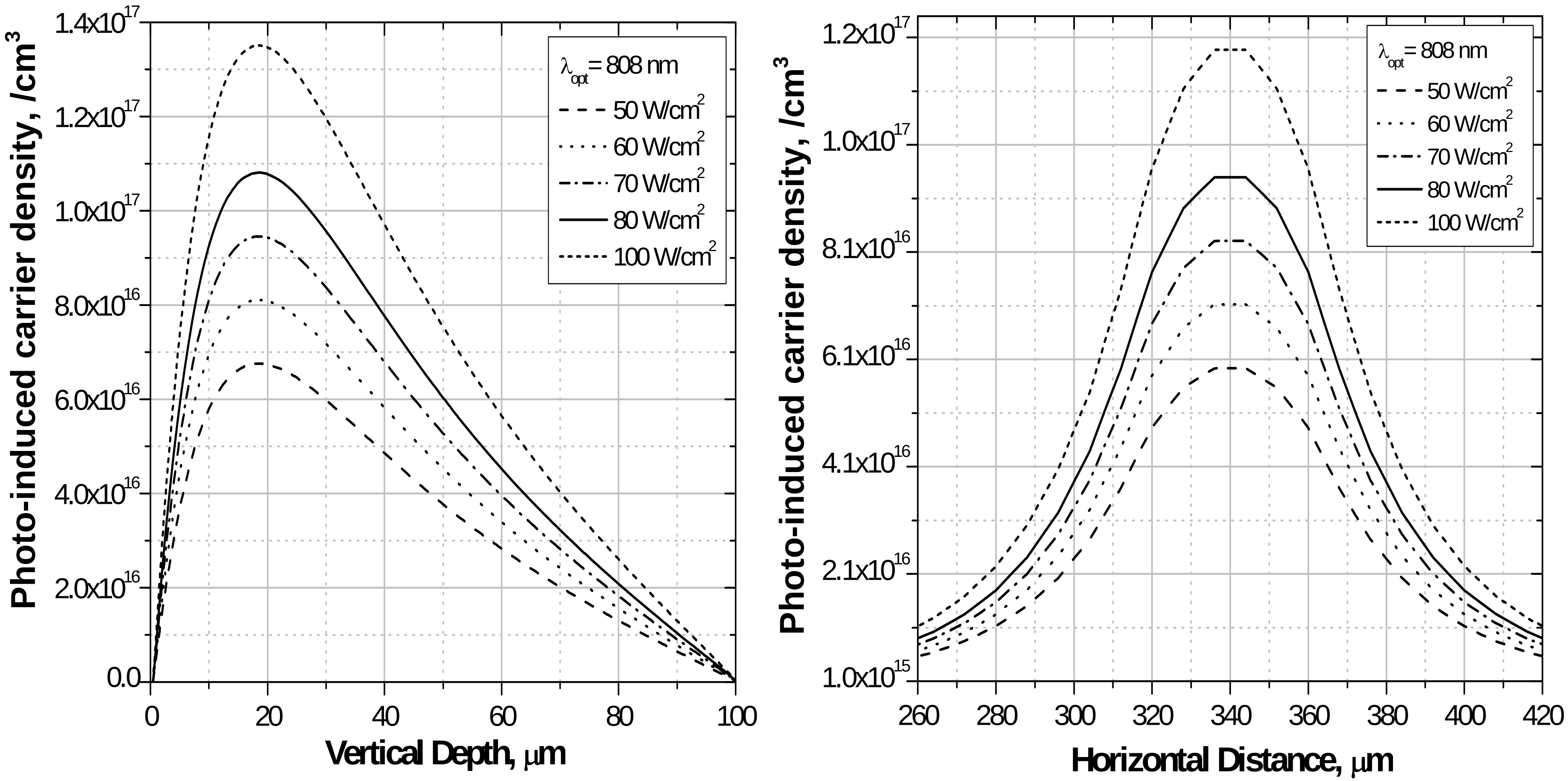

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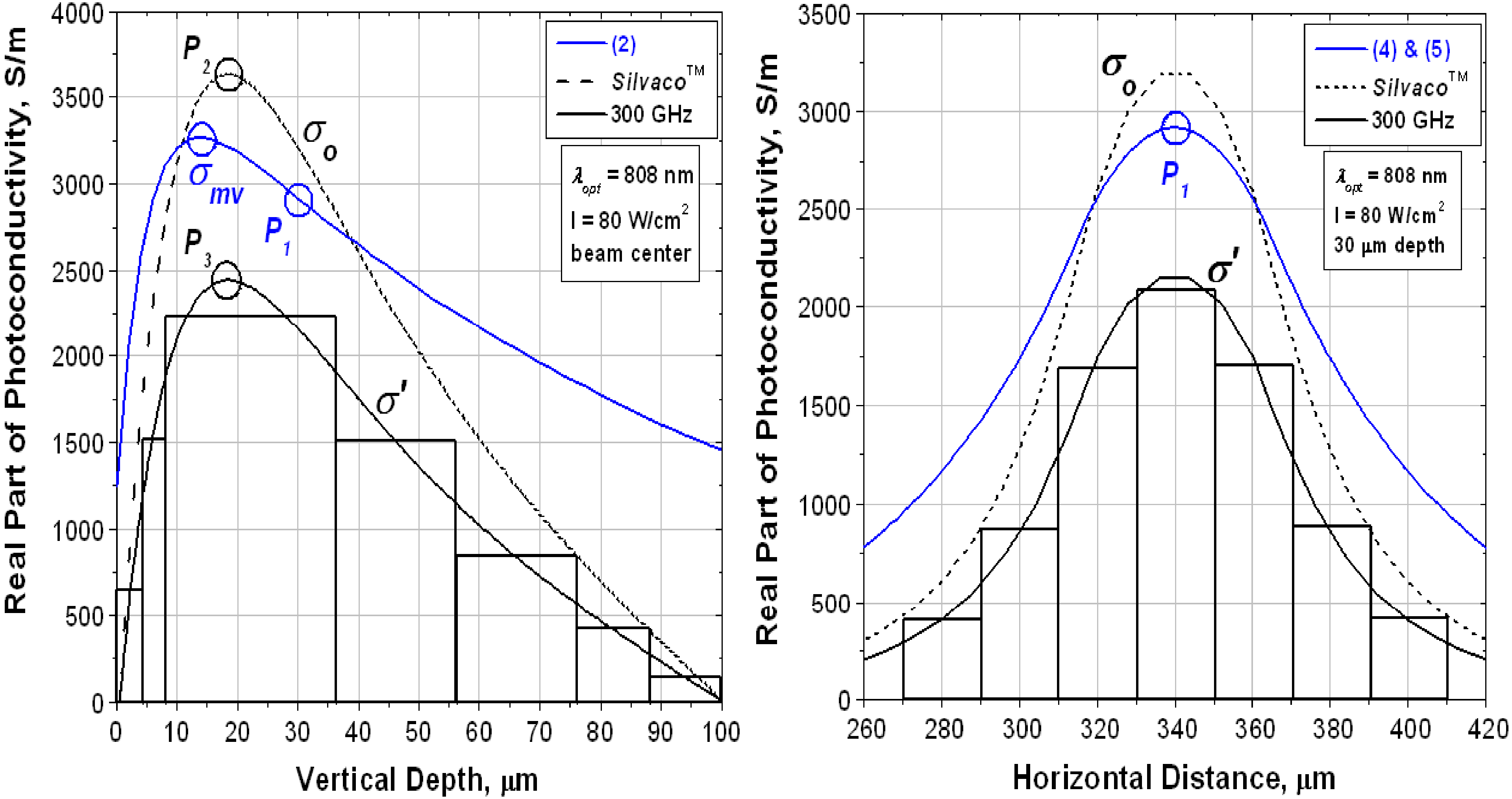

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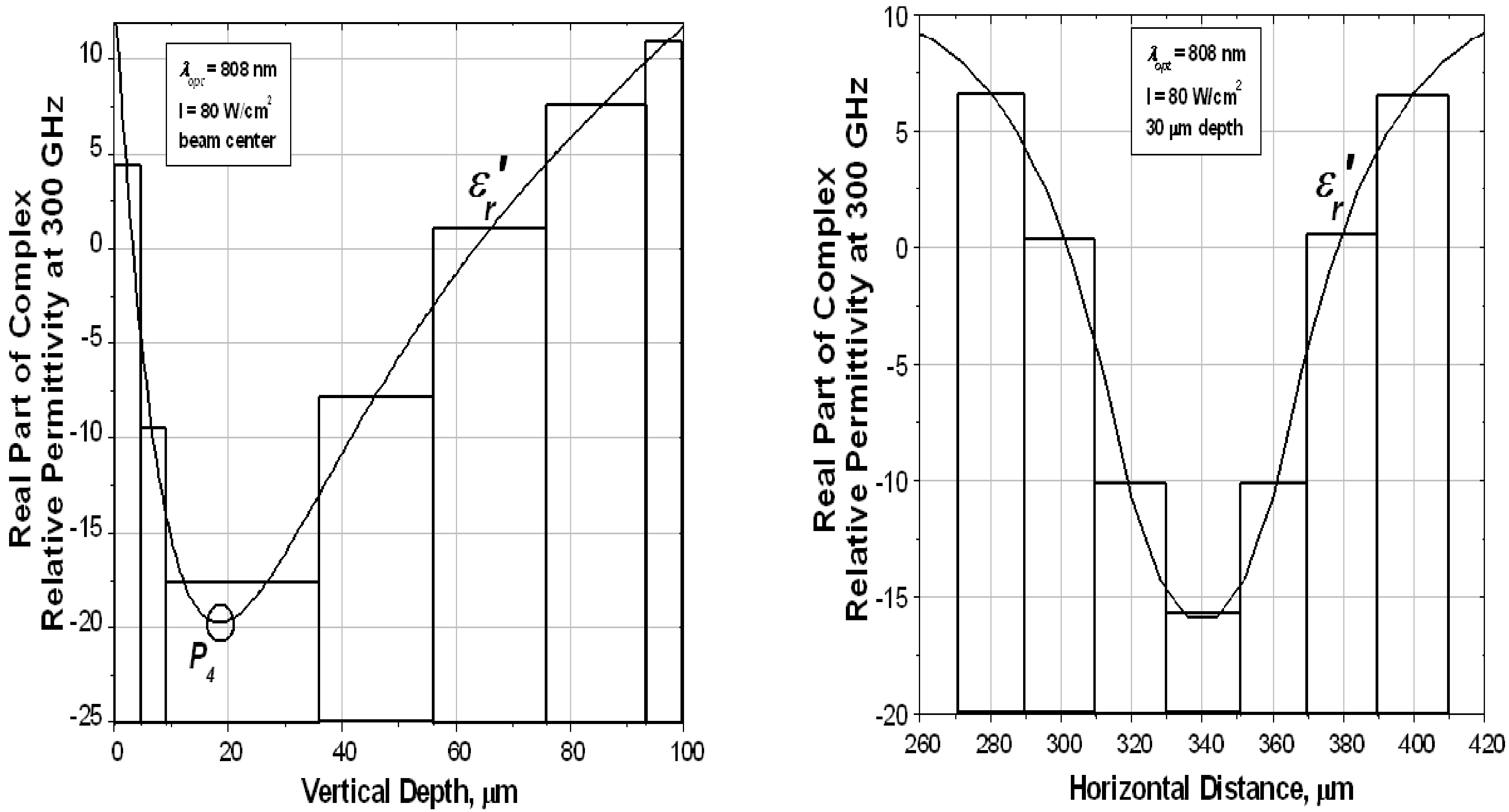
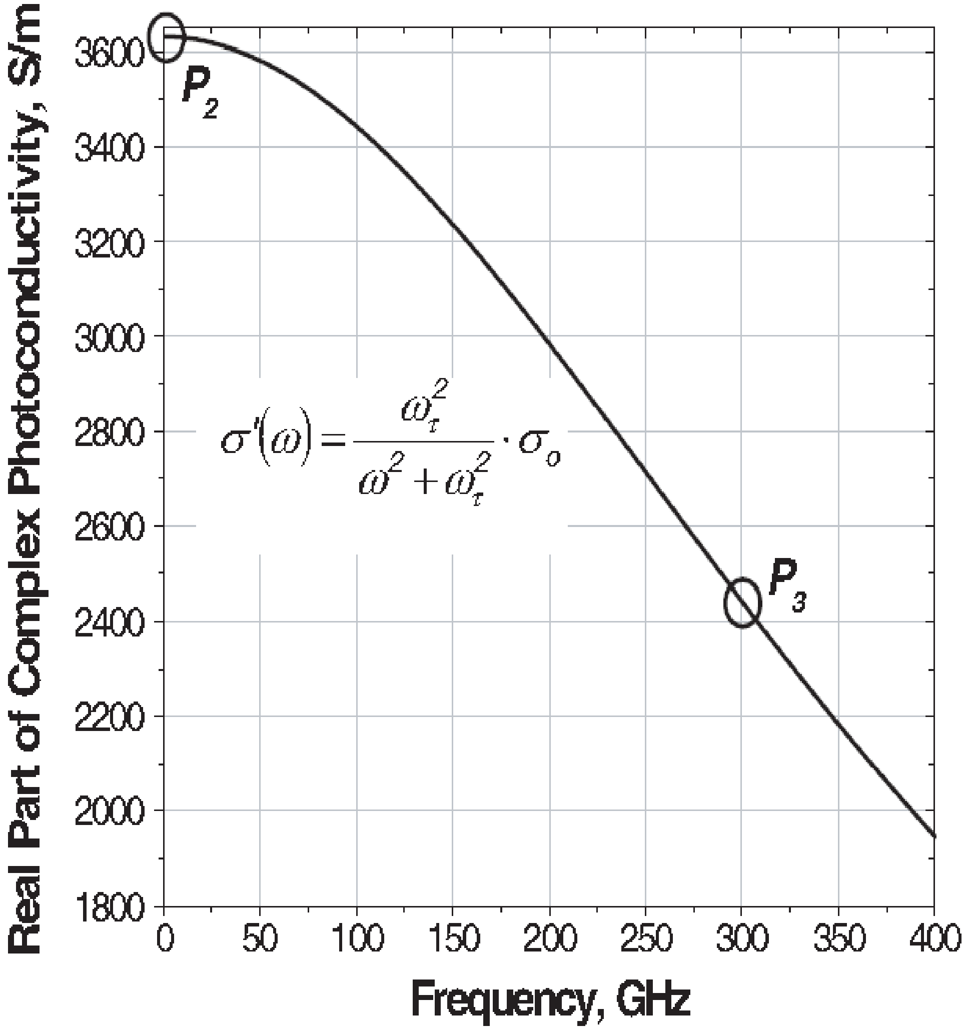
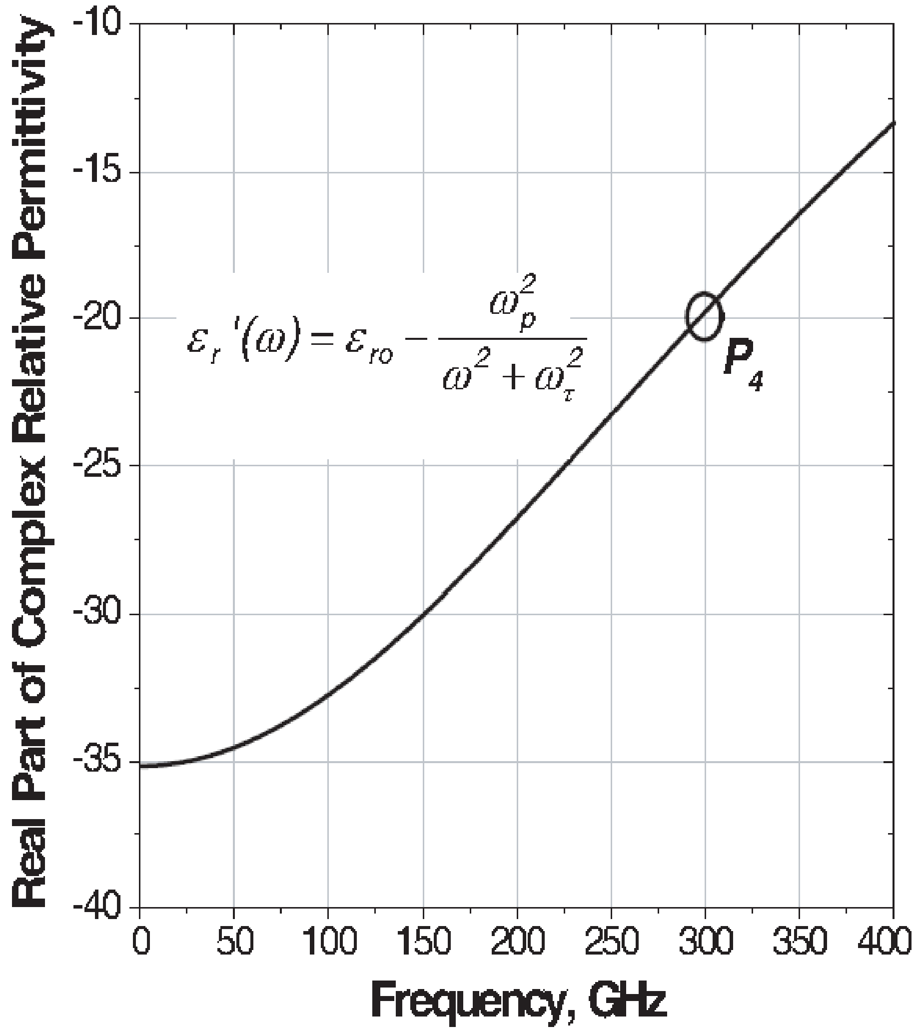



Real Part of Complex Photoconductivity, S/m
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
0 50 100 150 200 250 300 350 400
Frequency, GHz
P2
P3
$\sigma'(\omega) = \frac{\omega_\tau^2}{\omega^2 + \omega_\tau^2} \cdot \sigma_o$


Real Part of Complex Relative Permittivity
-10
-15
-20
-25
-30
-35
-40
0 50 100 150 200 250 300 350 400
Frequency, GHz
P4
$\varepsilon_r'(\omega) = \varepsilon_{ro} - \frac{\omega_p^2}{\omega^2 + \omega_\tau^2}$

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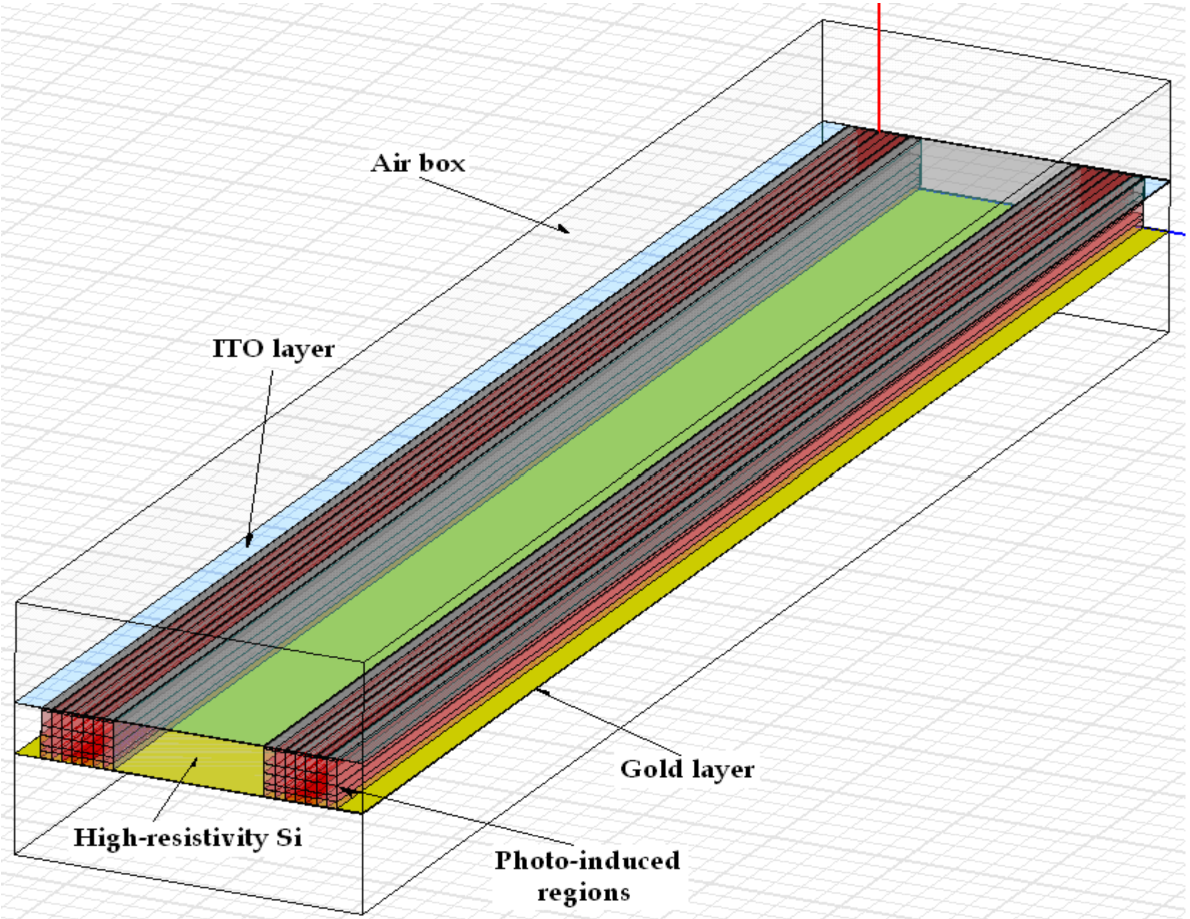
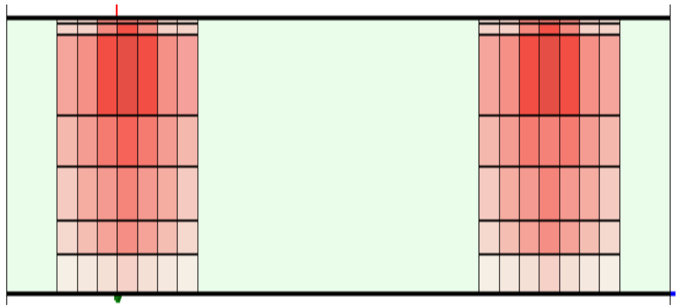
Electromagnetic Modelling

HFSS™ simulations: comparison with two beams



Single Sided



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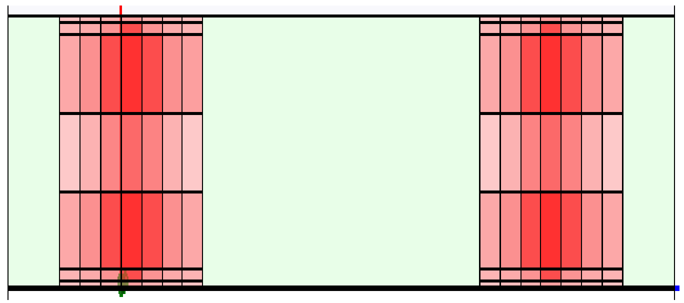

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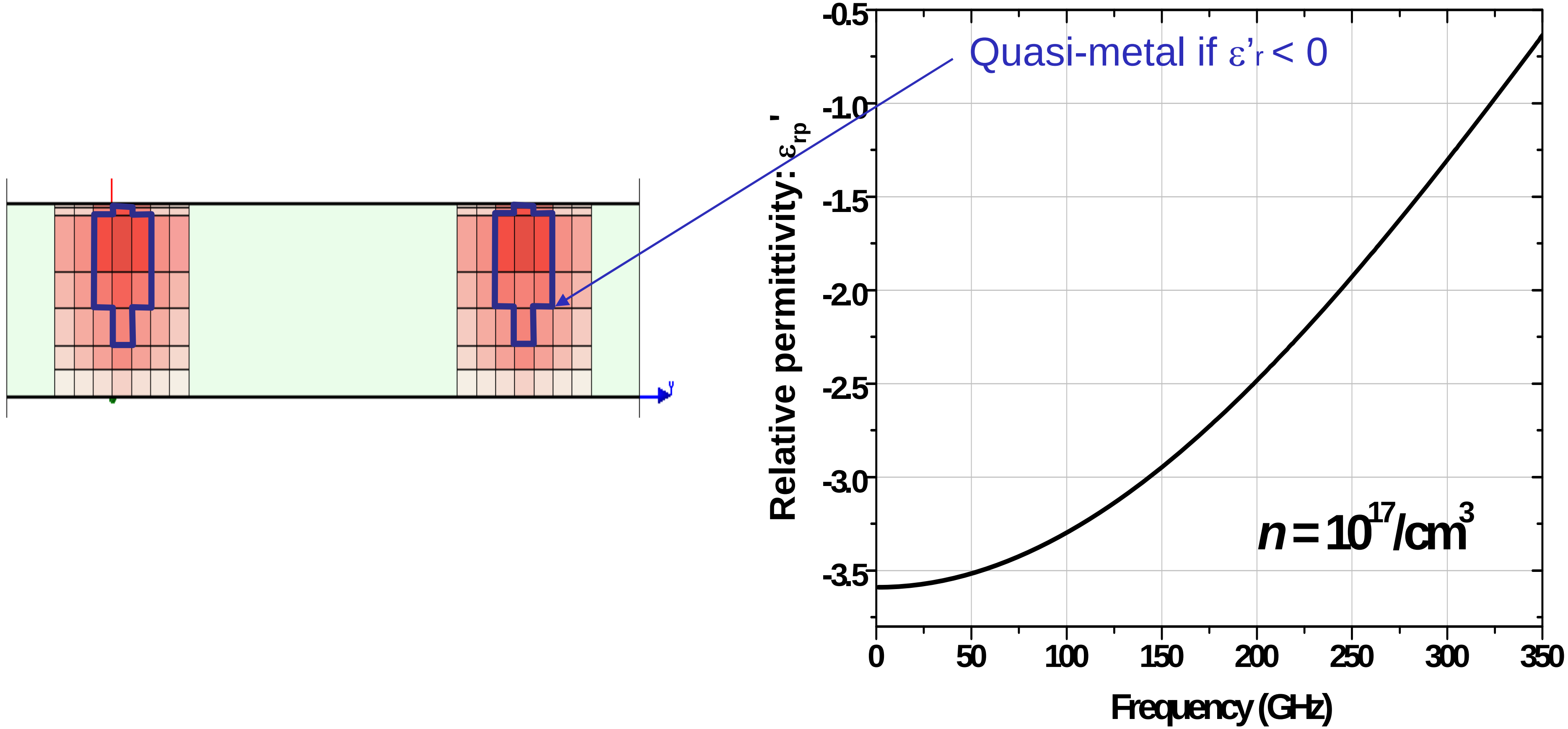
Wall Permittivity Modelling for Single-Sided Illumination



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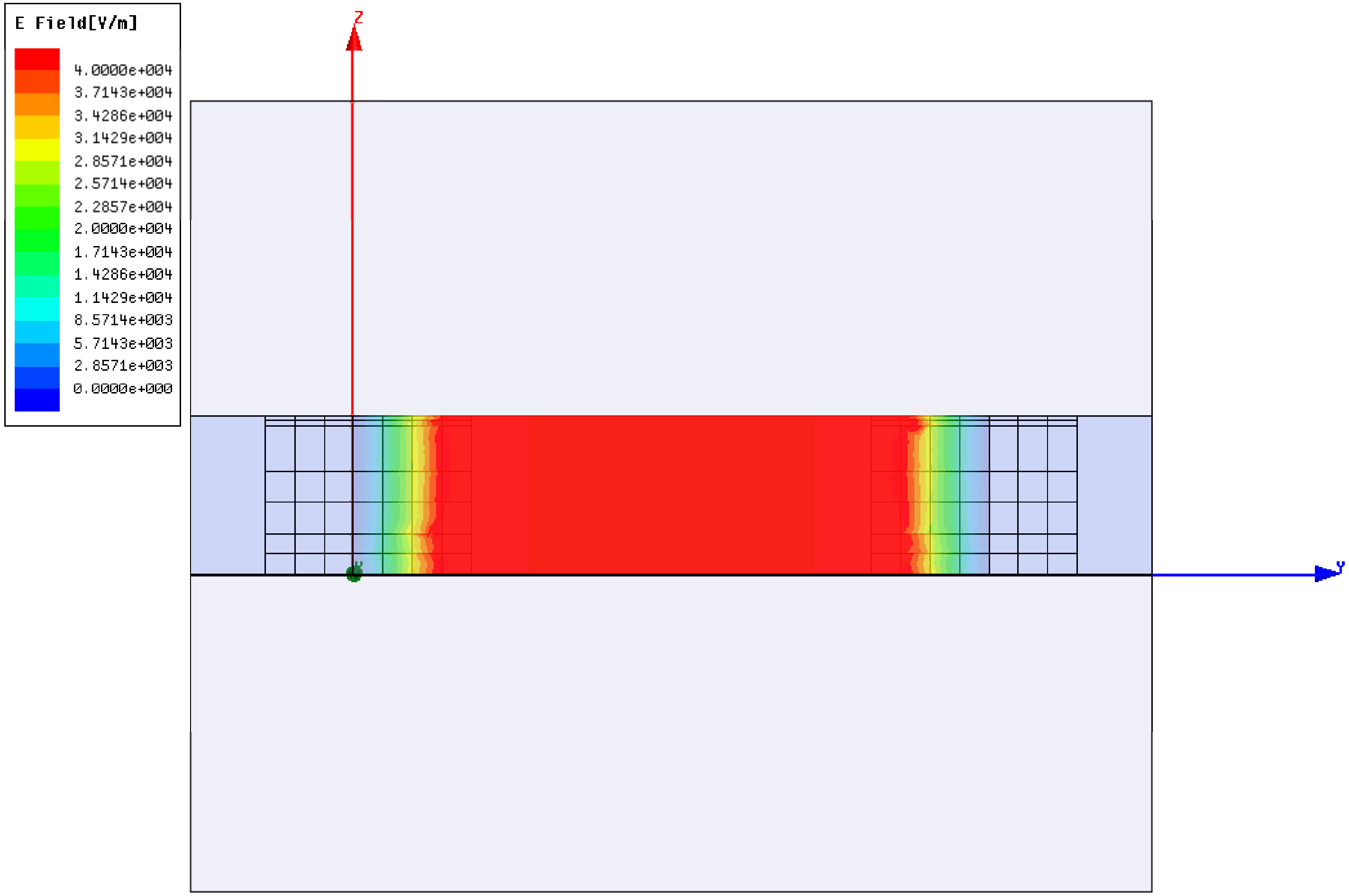
✍ Single Sided at 300 GHz



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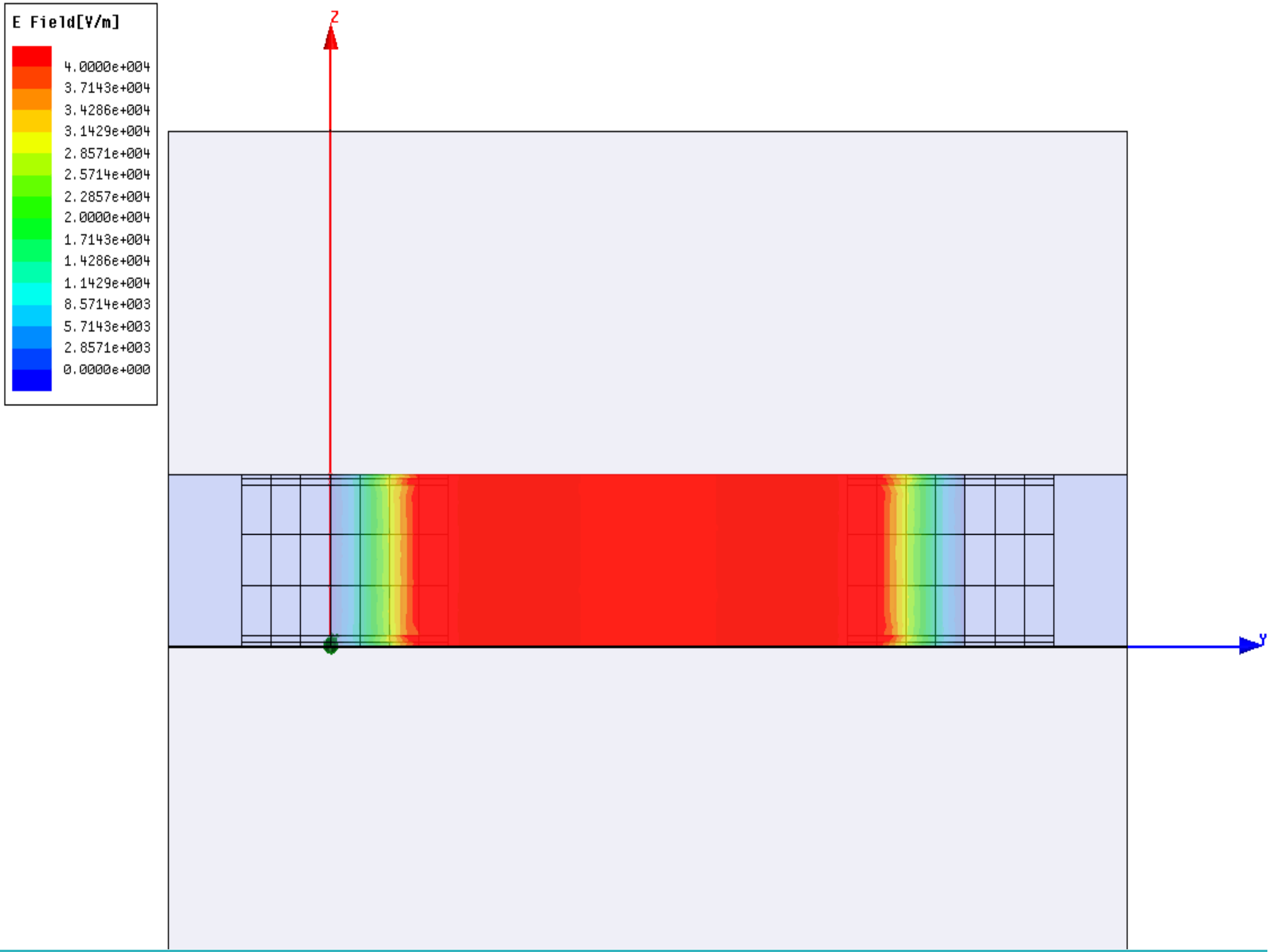
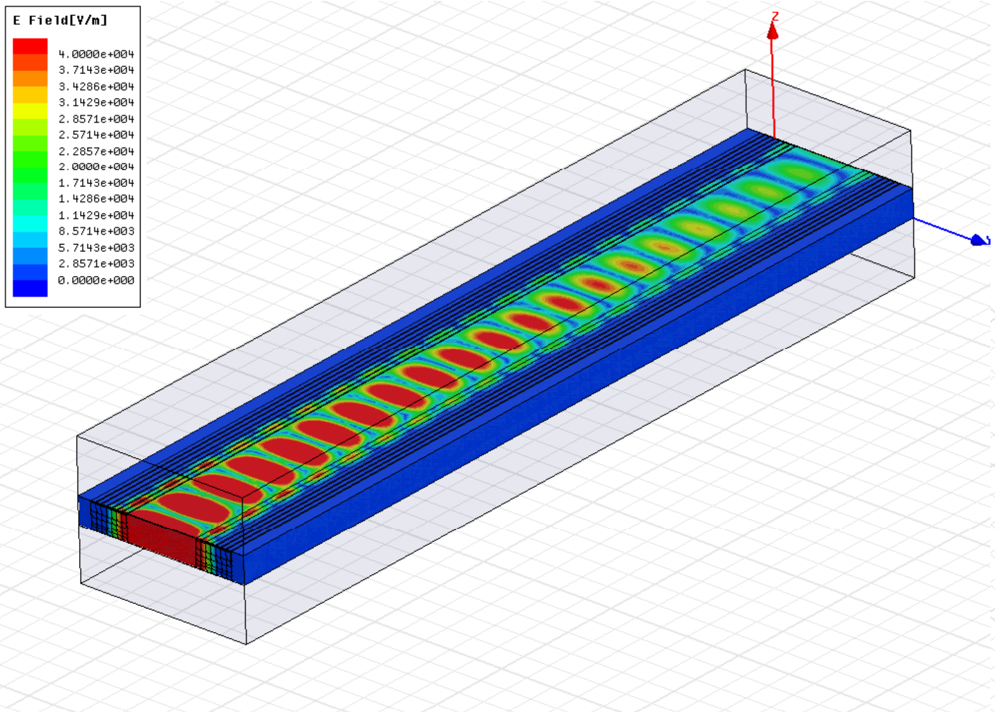
✍ Double Sided at 300 GHz

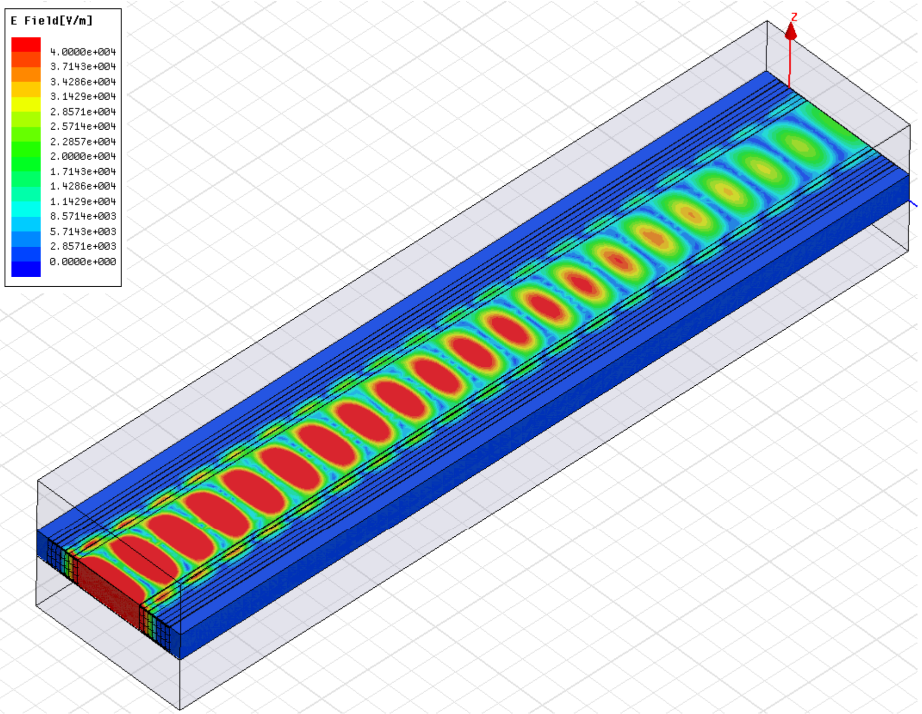


E-field Plots at 300 GHz

- Single Sided



- Double Sided



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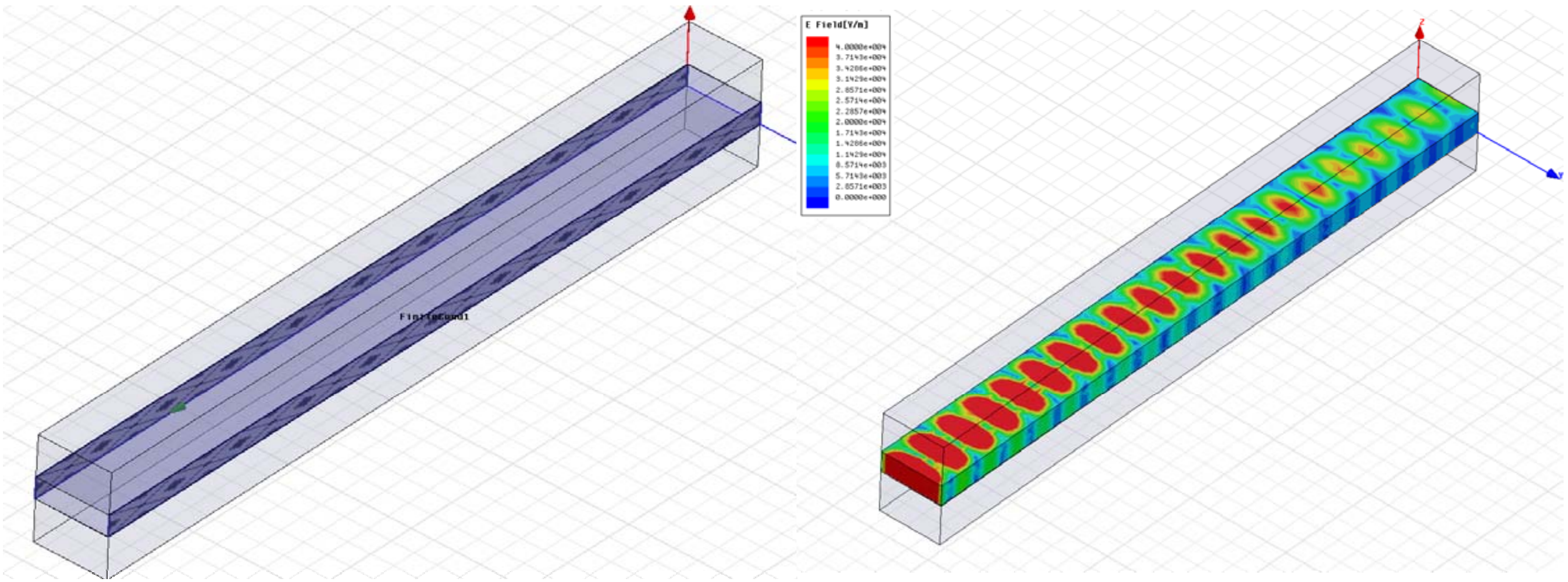
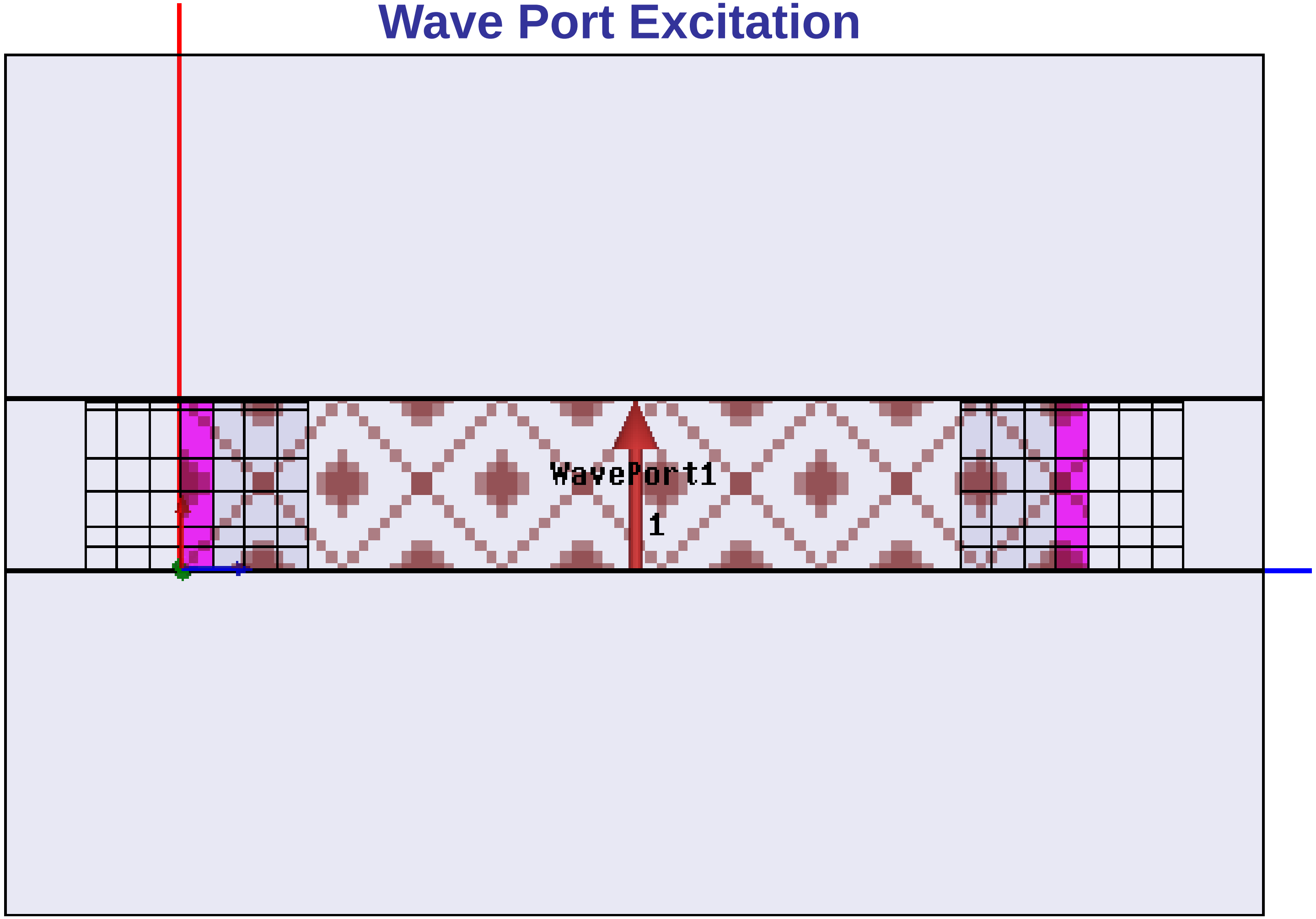
Wall Characterization

Equivalent Solid Wall



Wave Port Excitation



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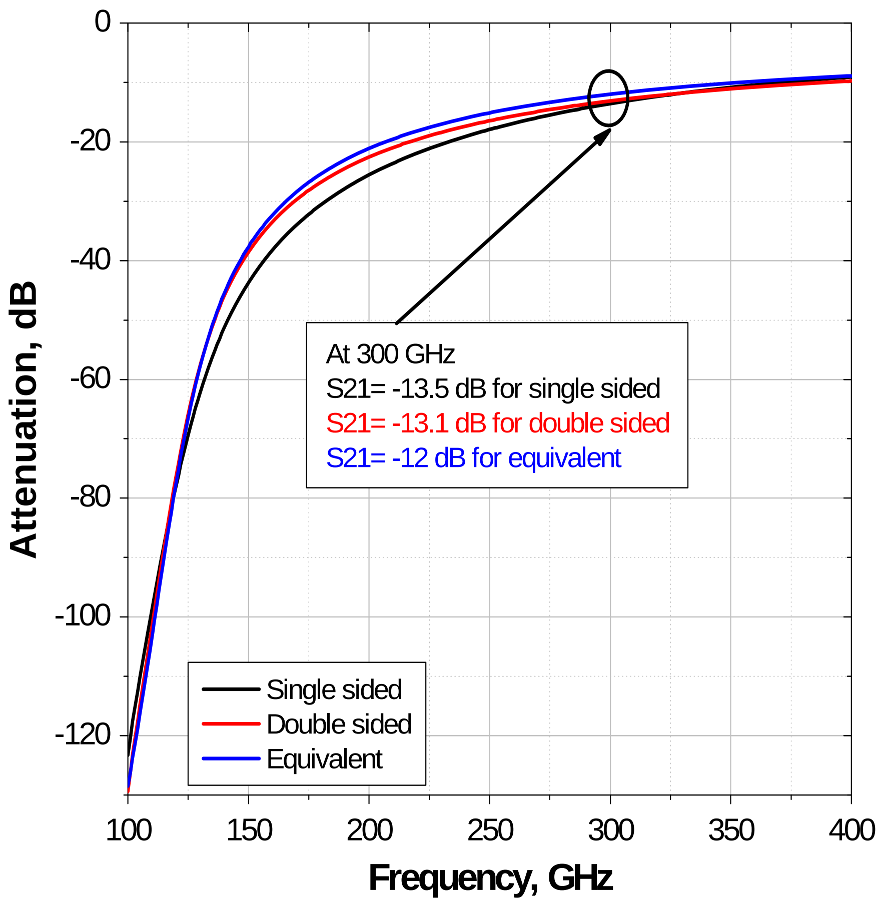

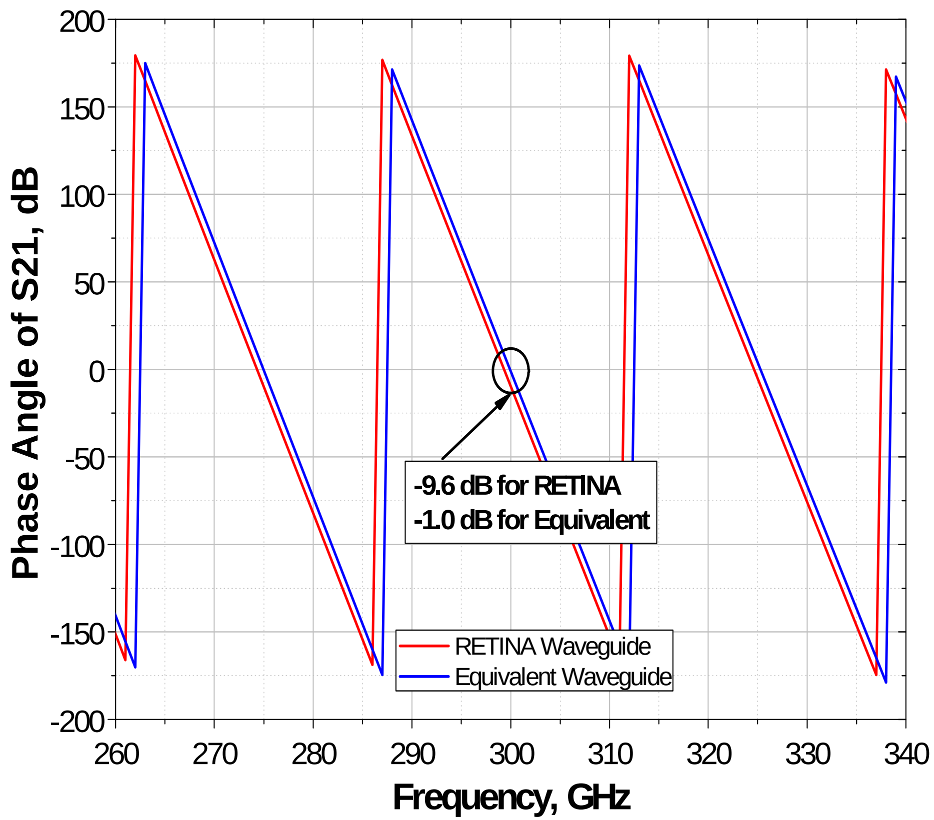

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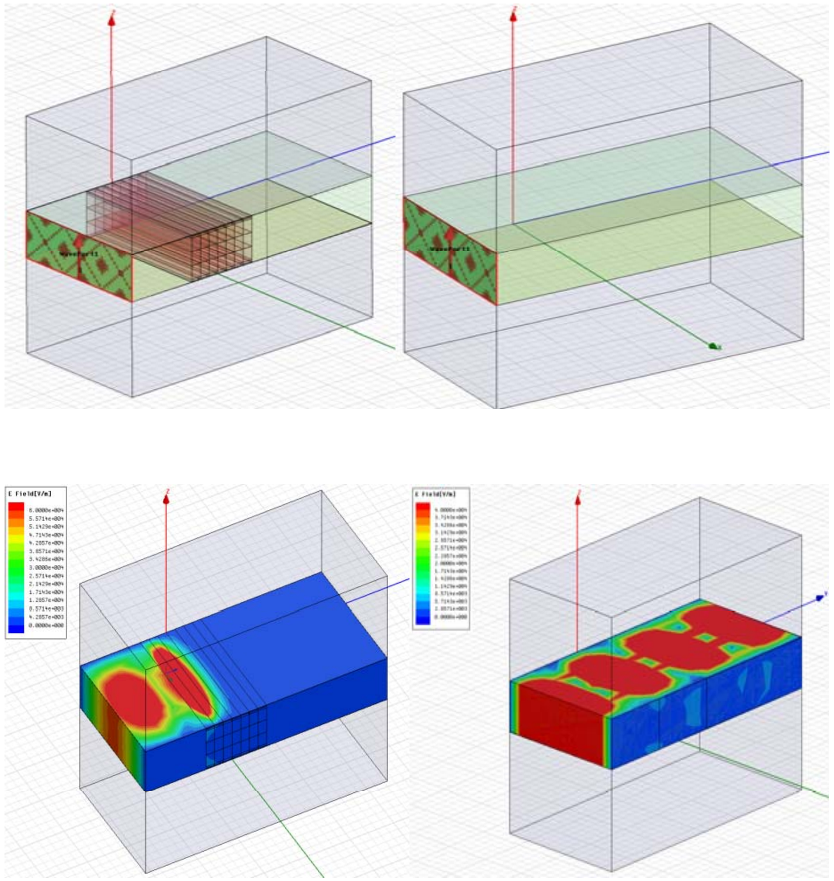
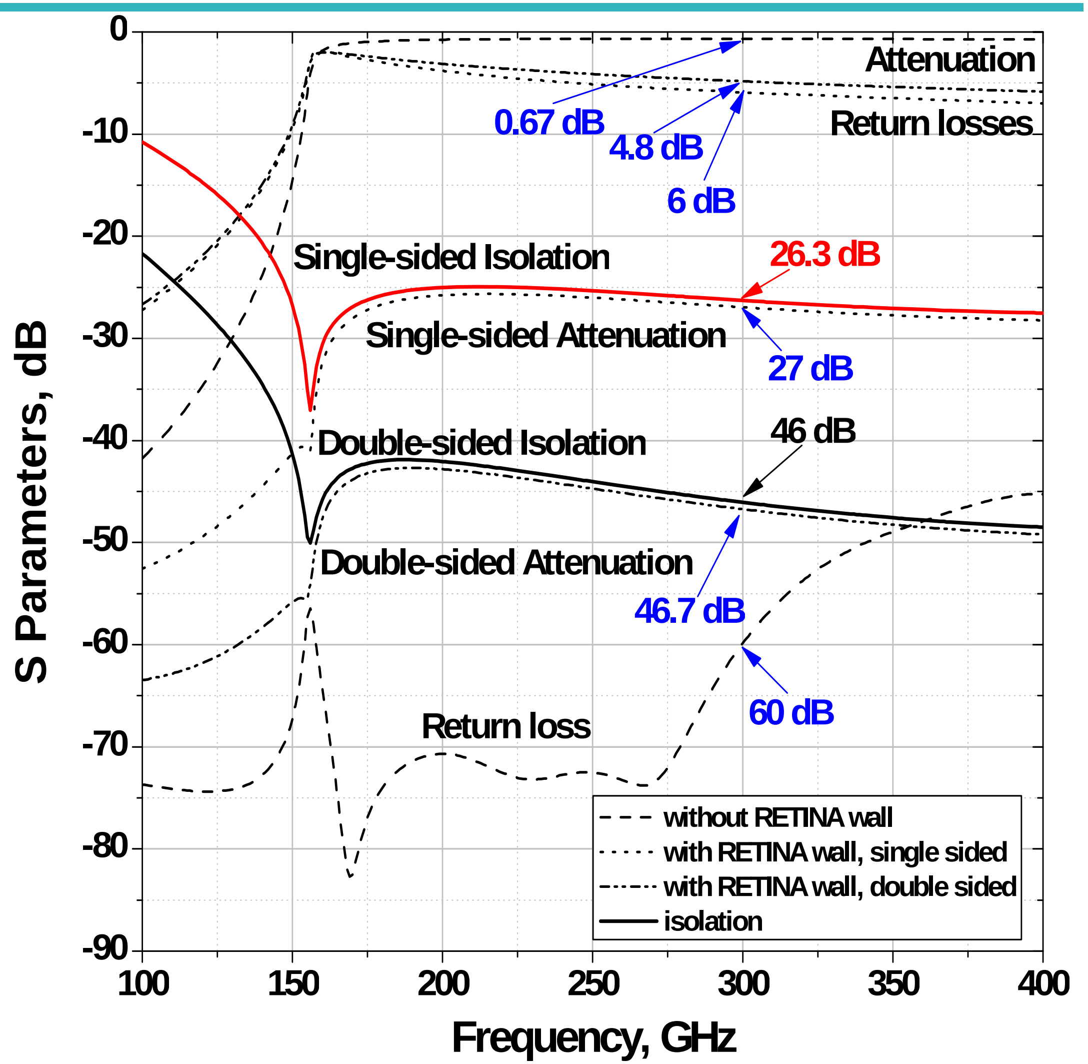
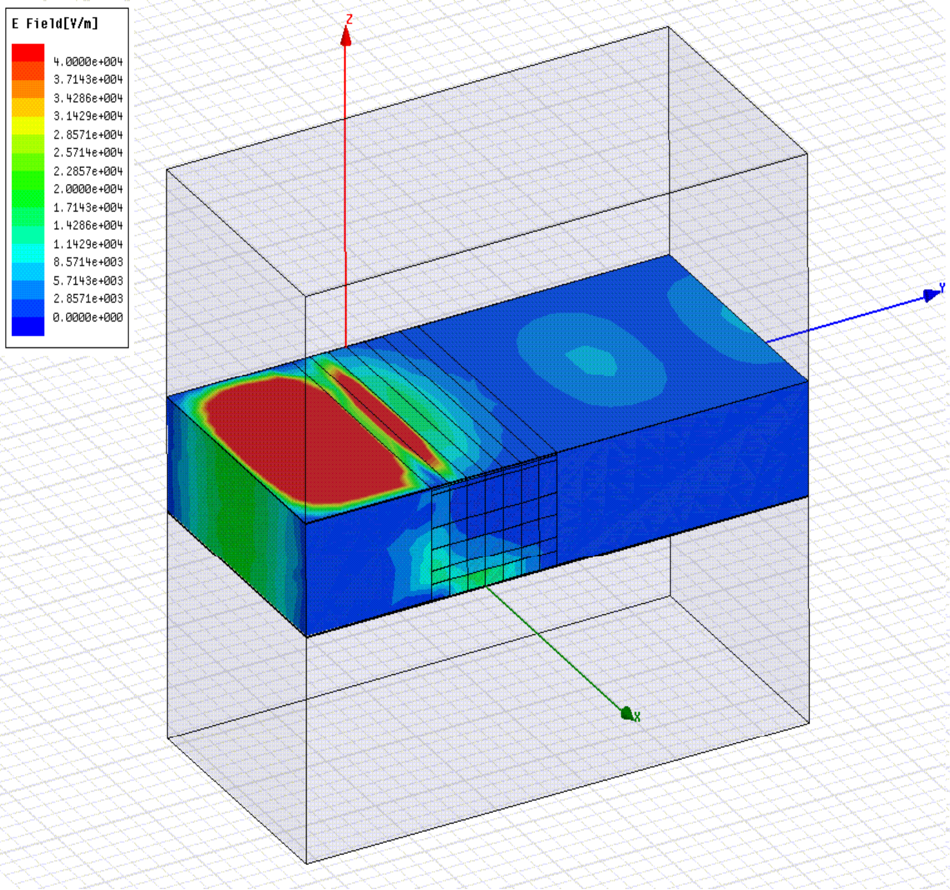
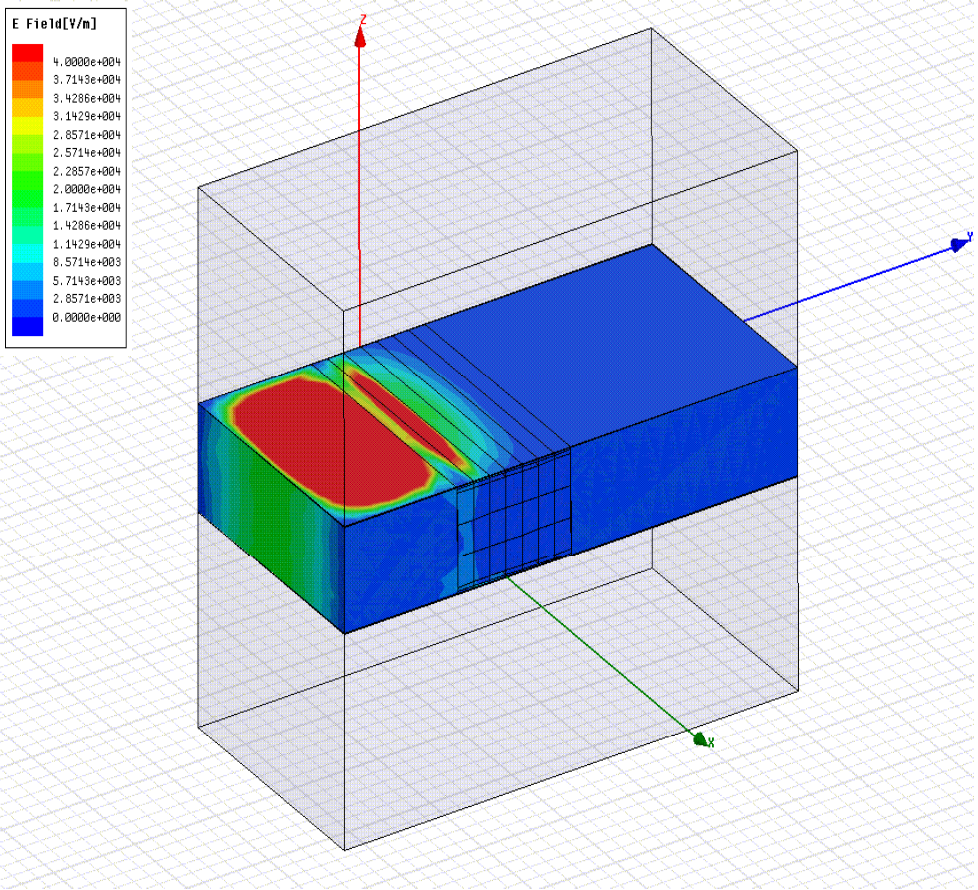
RETINA Wall Characterization






E Field[V/m]
4.0000e+004
3.7143e+004
3.4286e+004
3.1429e+004
2.8571e+004
2.5714e+004
2.2857e+004
2.0000e+004
1.7143e+004
1.4286e+004
1.1429e+004
8.5714e+003
5.7143e+003
2.8571e+003
0.0000e+000
Z
Y
X


E Field[V/m]
4.0000e+004
3.7143e+004
3.4286e+004
3.1429e+004
2.8571e+004
2.5714e+004
2.2857e+004
2.0000e+004
1.7143e+004
1.4286e+004
1.1429e+004
8.5714e+003
5.7143e+003
2.8571e+003
0.0000e+000
Z
Y
X

Loss Comparison with Various Non-Tuneable/Reconfigurable SIW Technologies

Technology	Frequency (GHz)	Insertion loss (dB/mm)	Conductor loss scaling to 300 GHz (dB/mm)
Alumina SIW	50	0.03	0.07
Ceramic (HT1000) SIW	60	0.20	0.45
Ceramic (QM44F) SIW	74	0.70	1.41
Polyimide (Kapton HN) SIW	79	0.17	0.33
Photoimageable Dielectric HD1000-filled MPRWG	83	1.2	2.3
Air-filled MPRWG	100	0.01	0.017
Polyimide-filled MPRWG	105	8.98	15.18
Air-filled MPRWG	400	0.086	0.074
RETINA (simulated)	300	3.88	3.88

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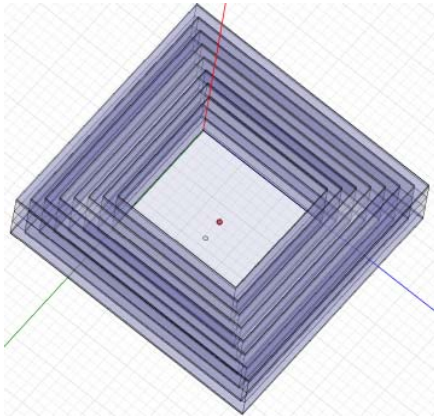
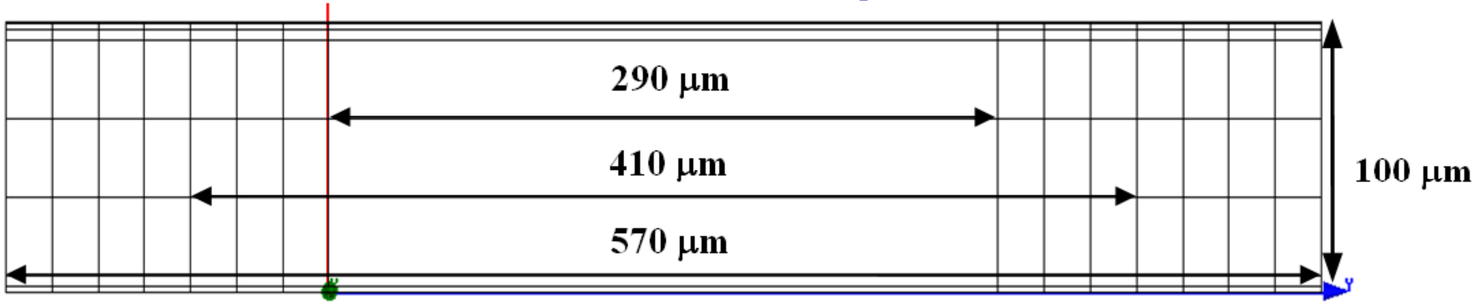
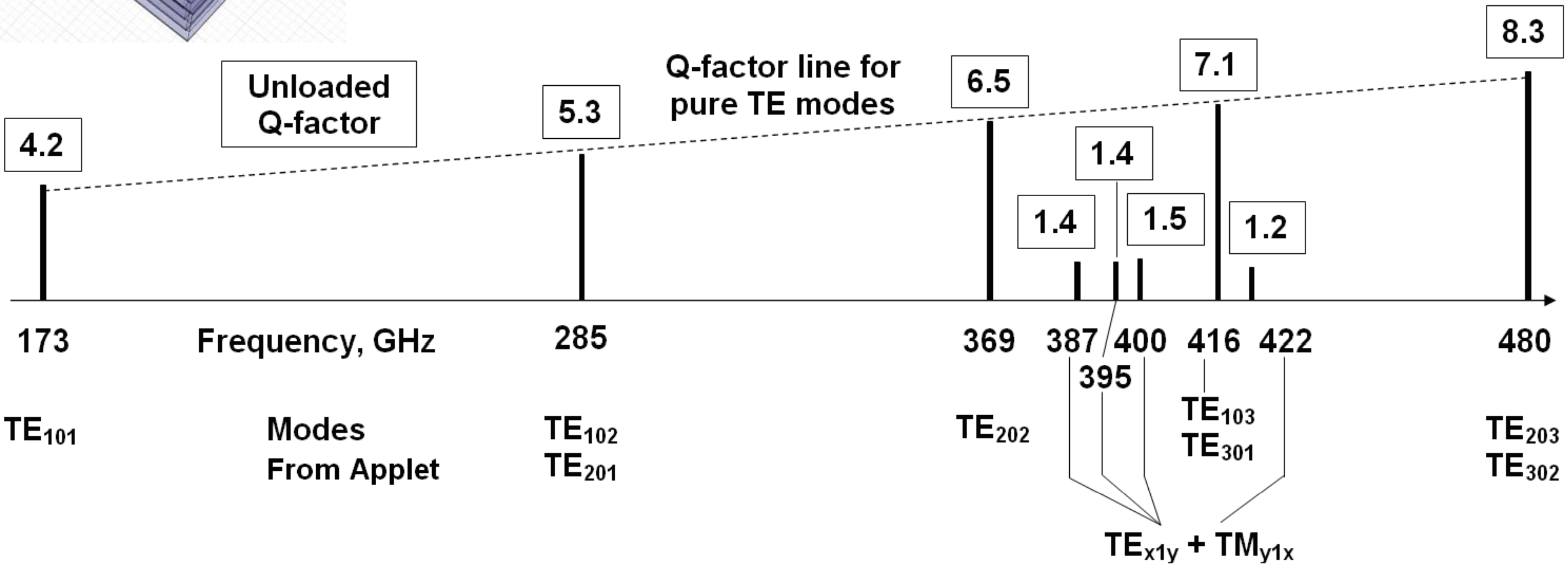
Cavity Resonators

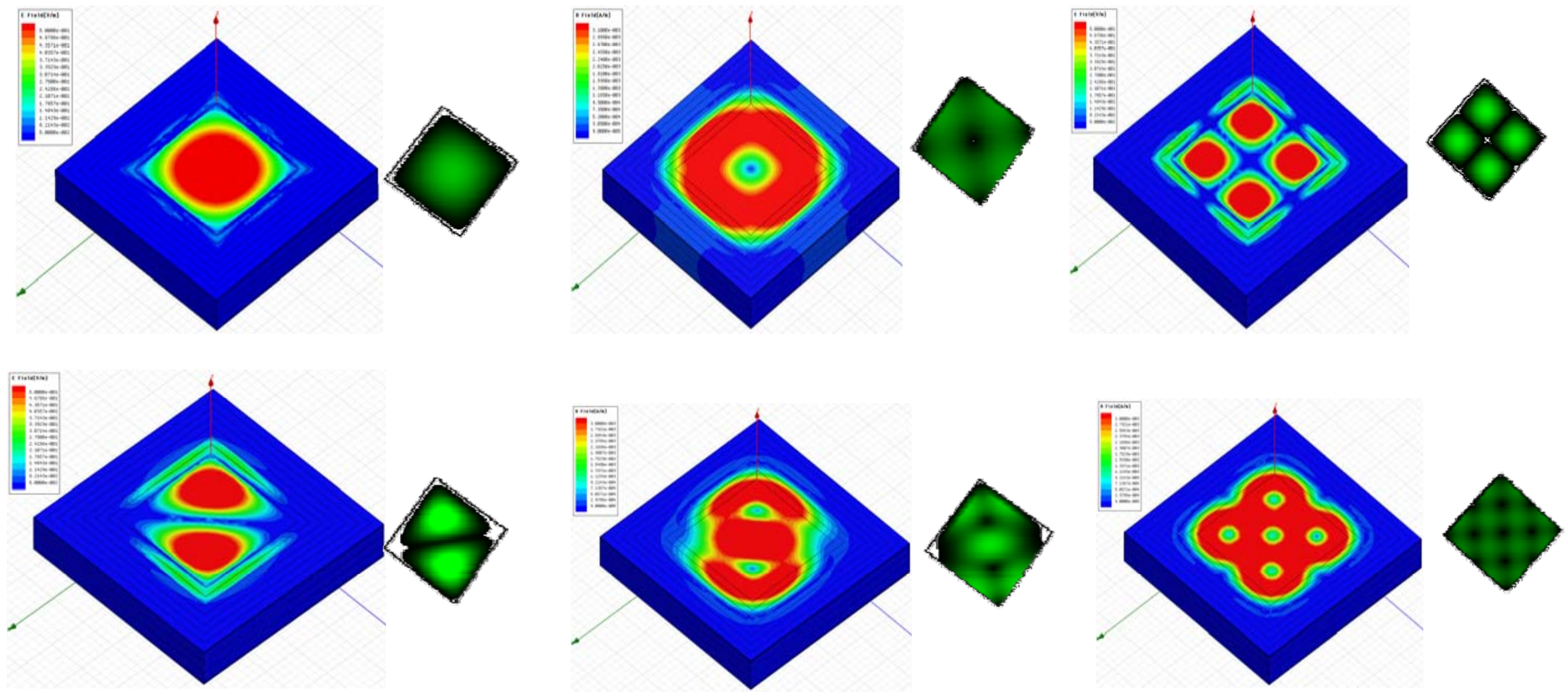
Double Sided RETINA Cavity Resonators



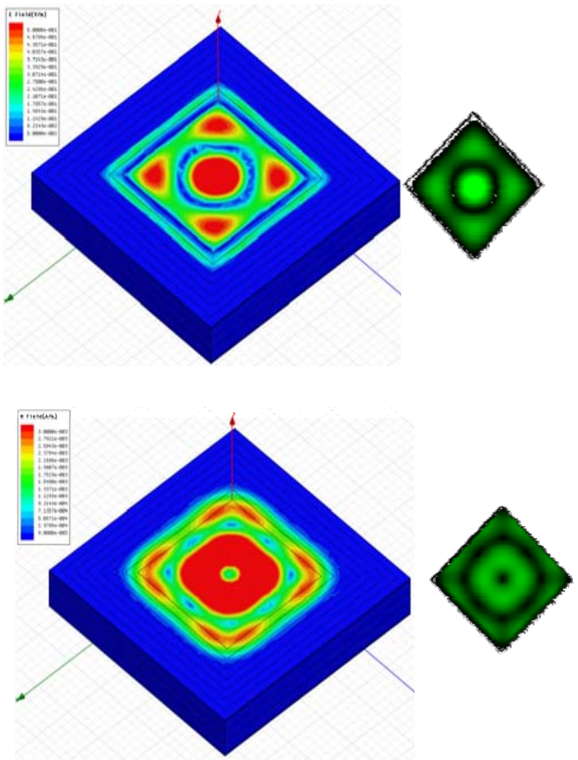




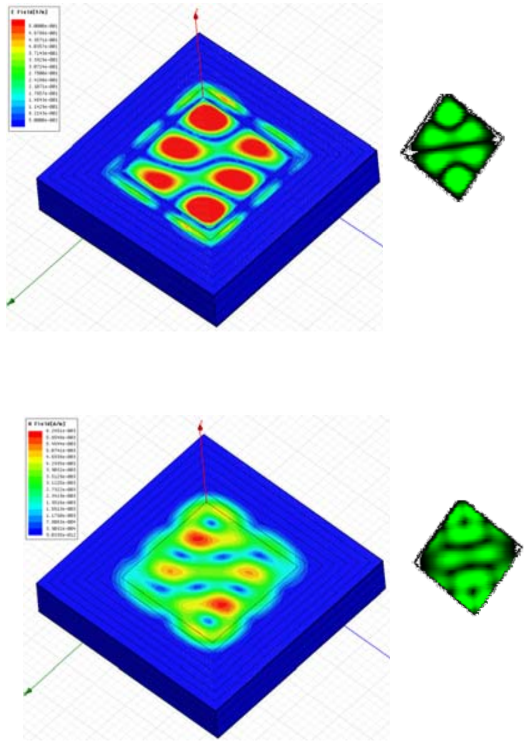
TE_{101} TE_{201} TE_{202}



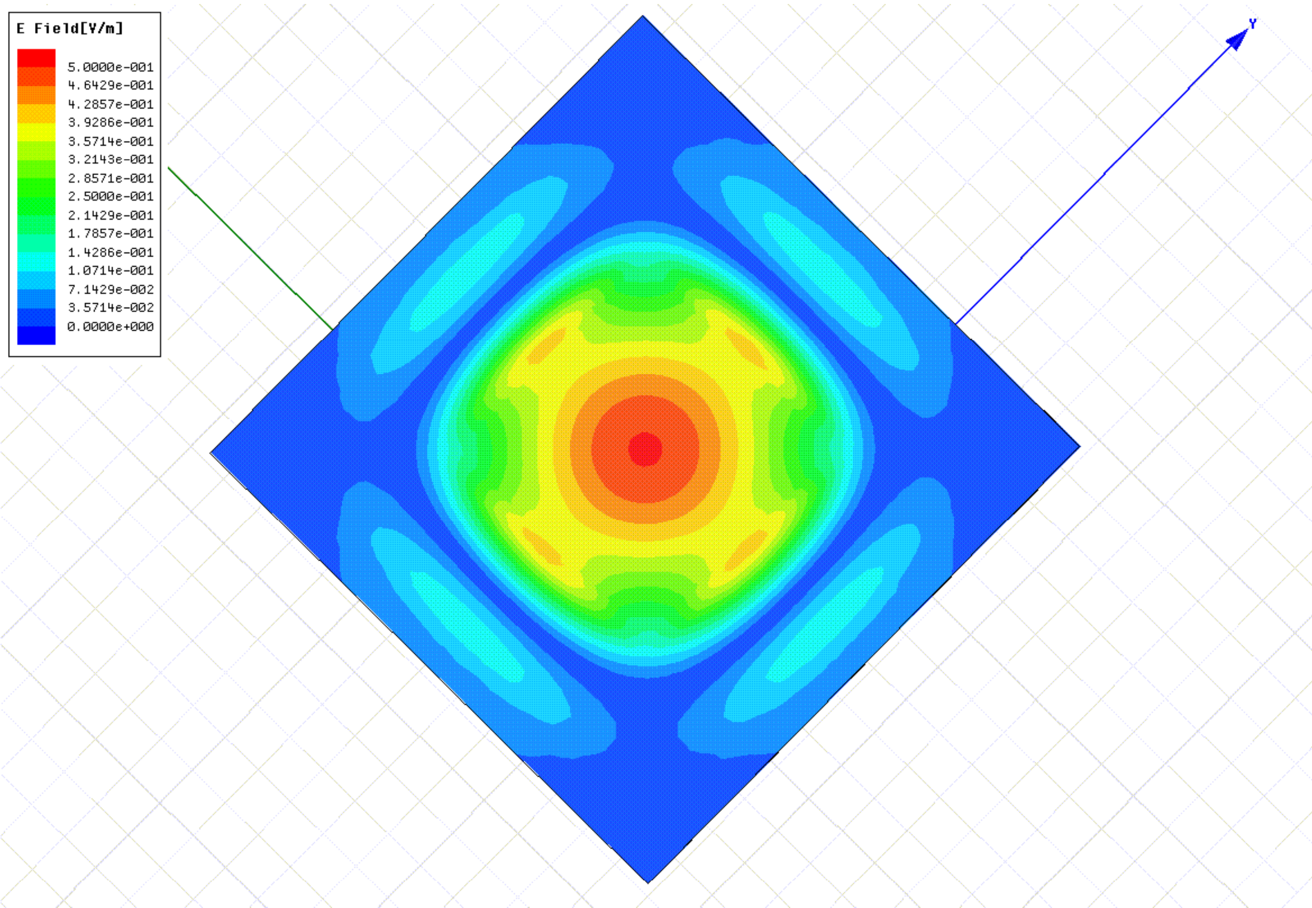
TE_{301}



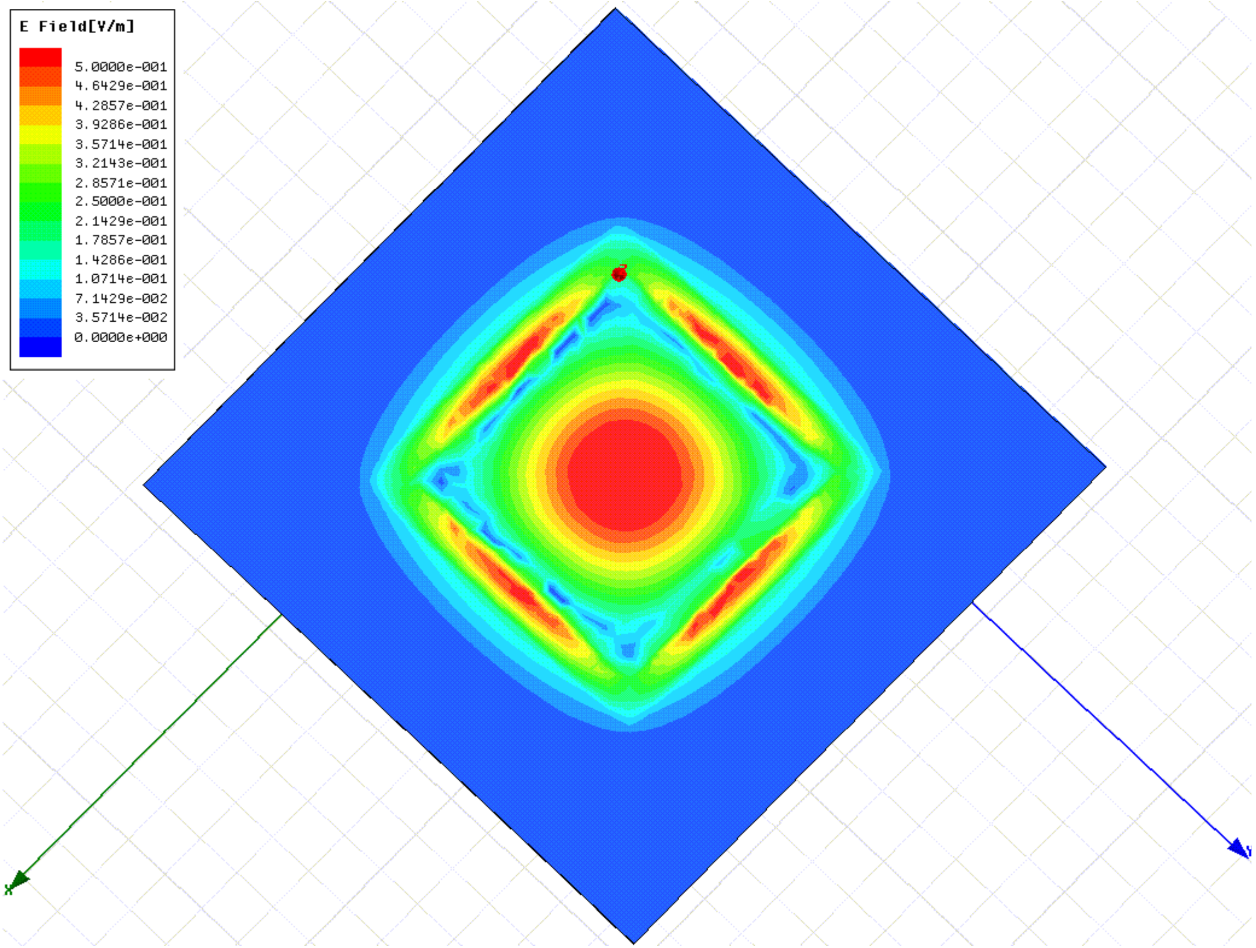
TE_{302}



✍Single Sided Backside for TE_{101} at 170 GHz



✍Double Sided Backside for TE_{101} at 174 GHz



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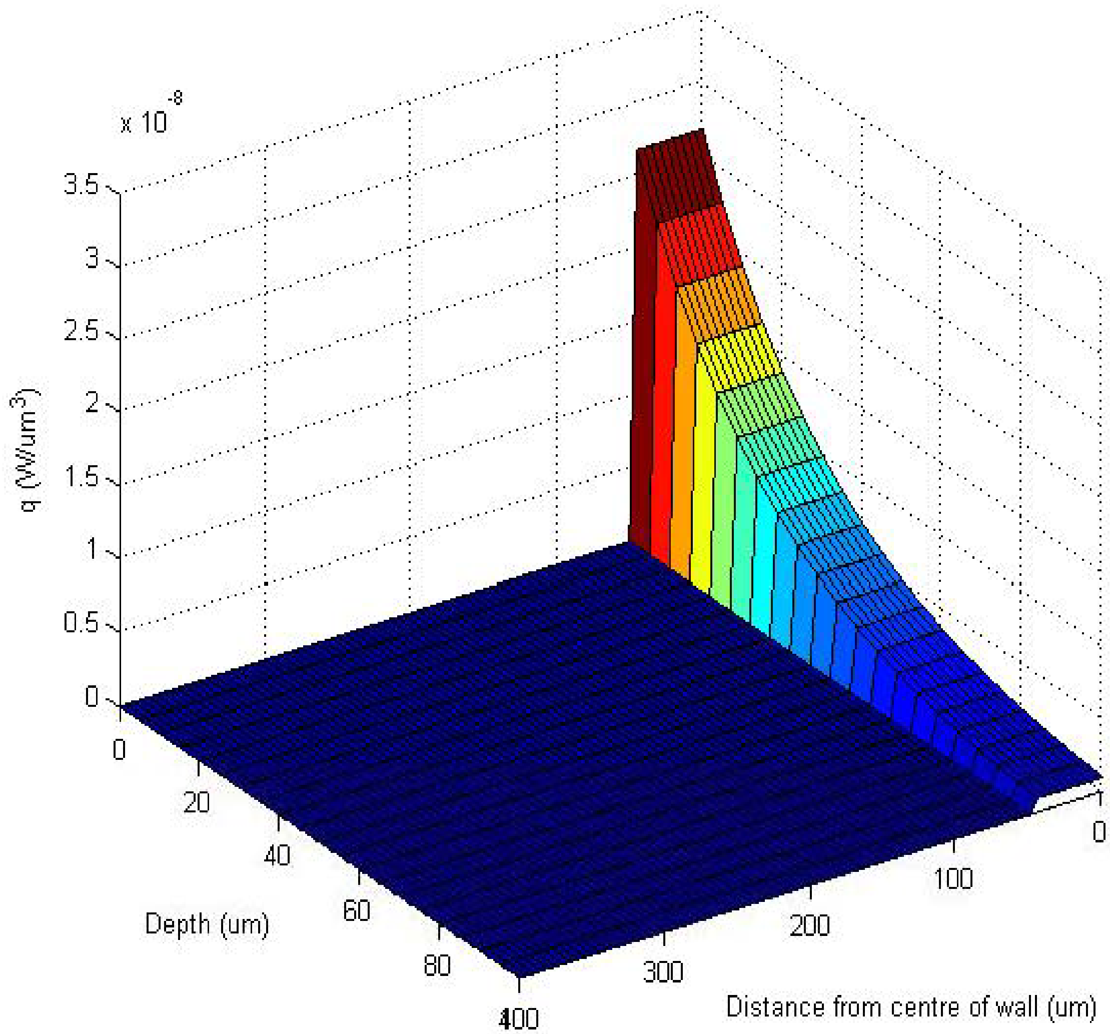
Thermal Modelling



✍ Using 2D finite difference solver in Matlab:

Distribution of heat generation due to light absorption, assuming:

- absorption length of 30 μm
- no reflection at the bottom of the substrate

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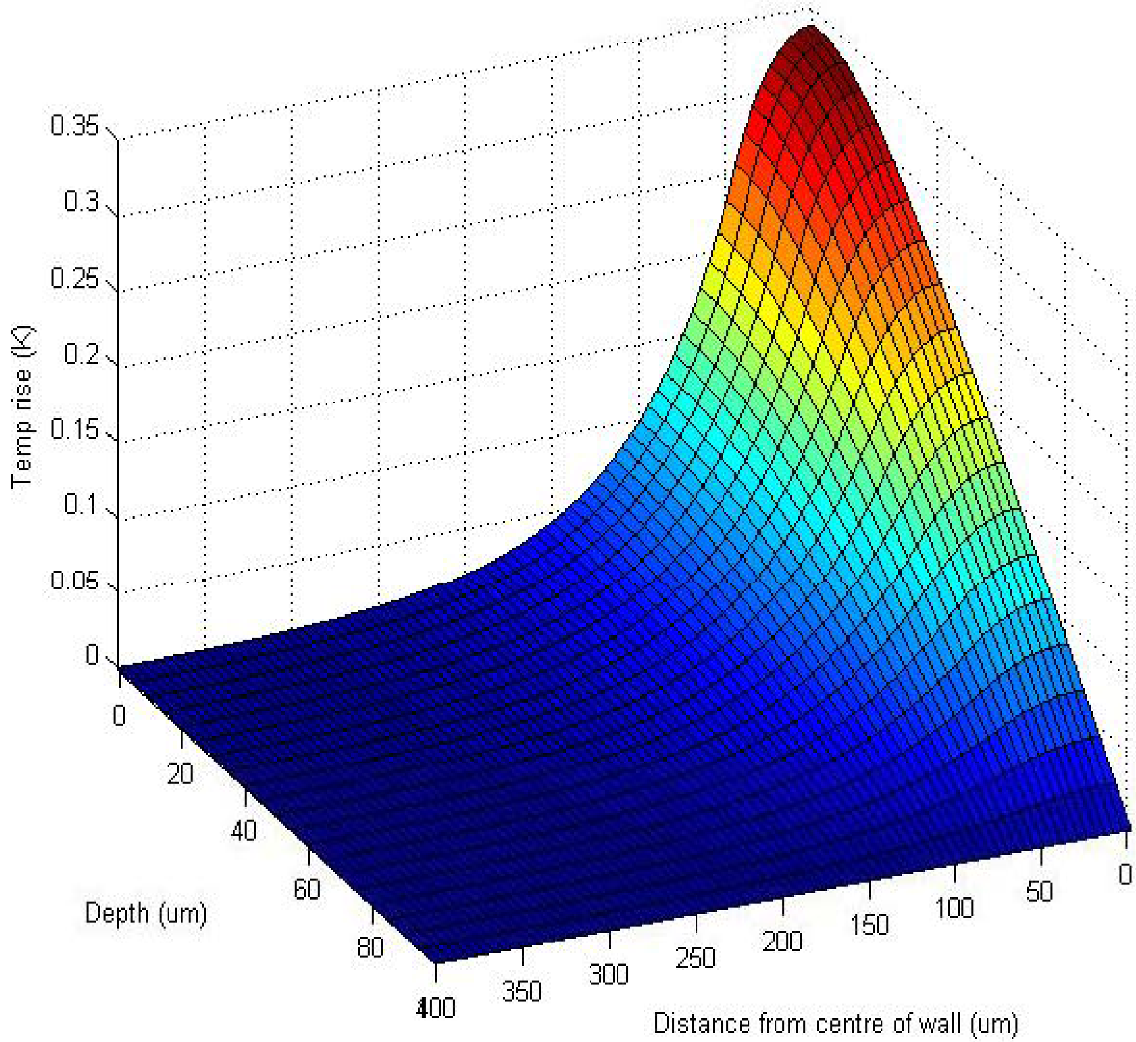

✍ Distribution of temperature rise for a 100 μm wide virtual wall in a 100 μm thick substrate:

- 80 W/cm² incident power
- good backside heatsink

Temperature rise in the RETINA substrate could be kept below 1ºC under realistic illumination conditions

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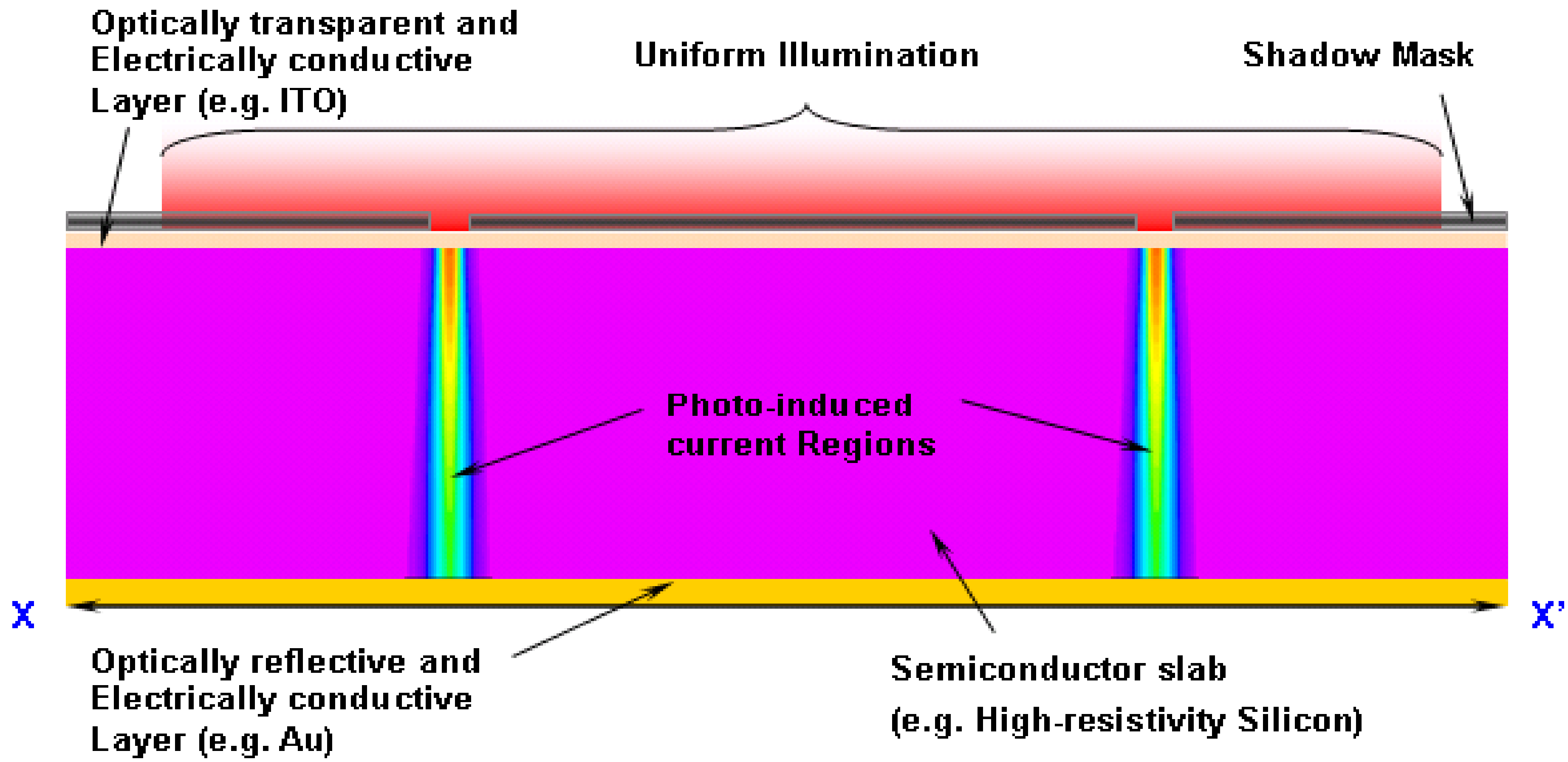
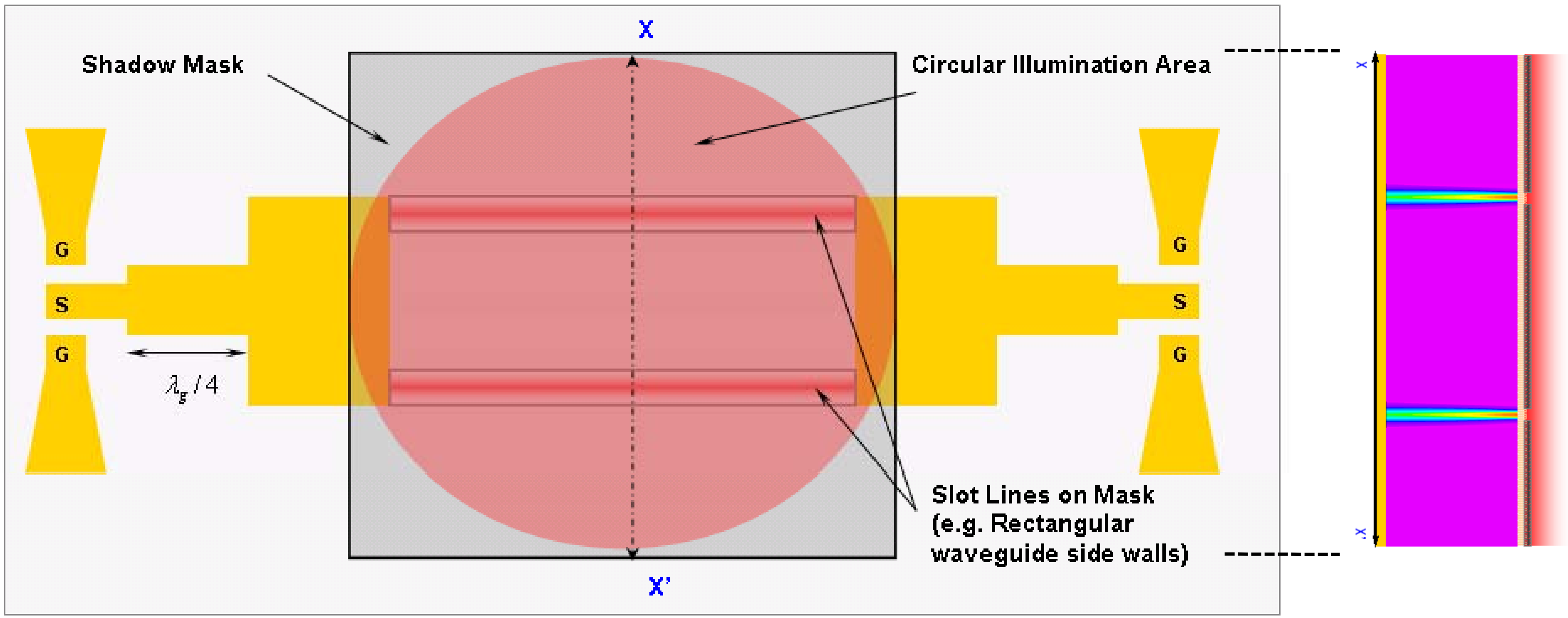
Proof of Concepts

✍ Simple proof-of-concept experiment at 200 GHz

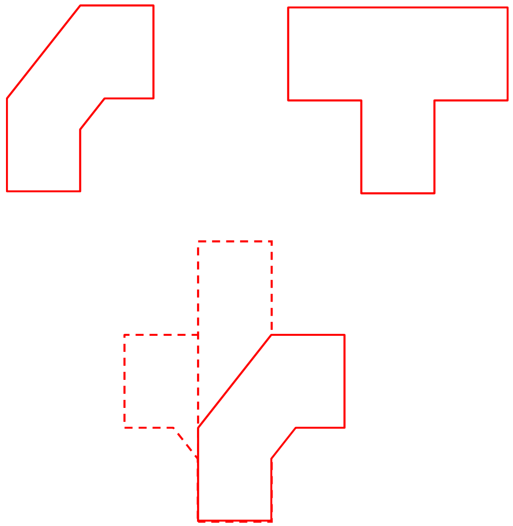


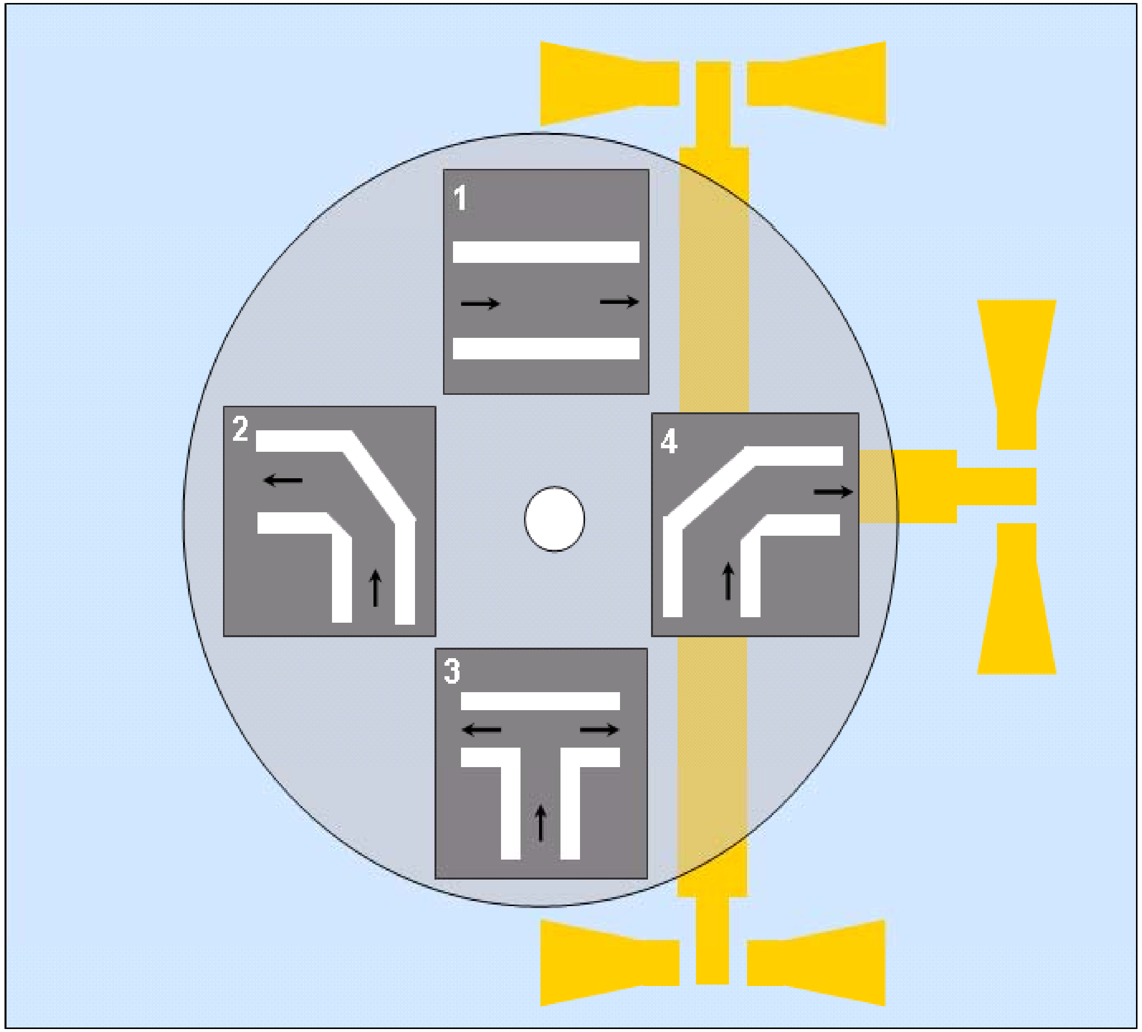
✍ MPRWG design for conventional on-wafer probing at 200 GHz



✍ RETINA exemplars:

- right-angled bends
- power splitters
- SP3T switches





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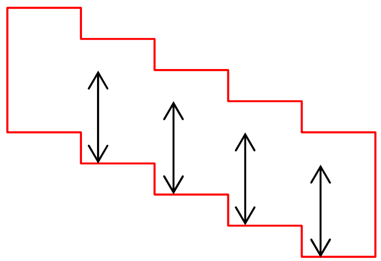
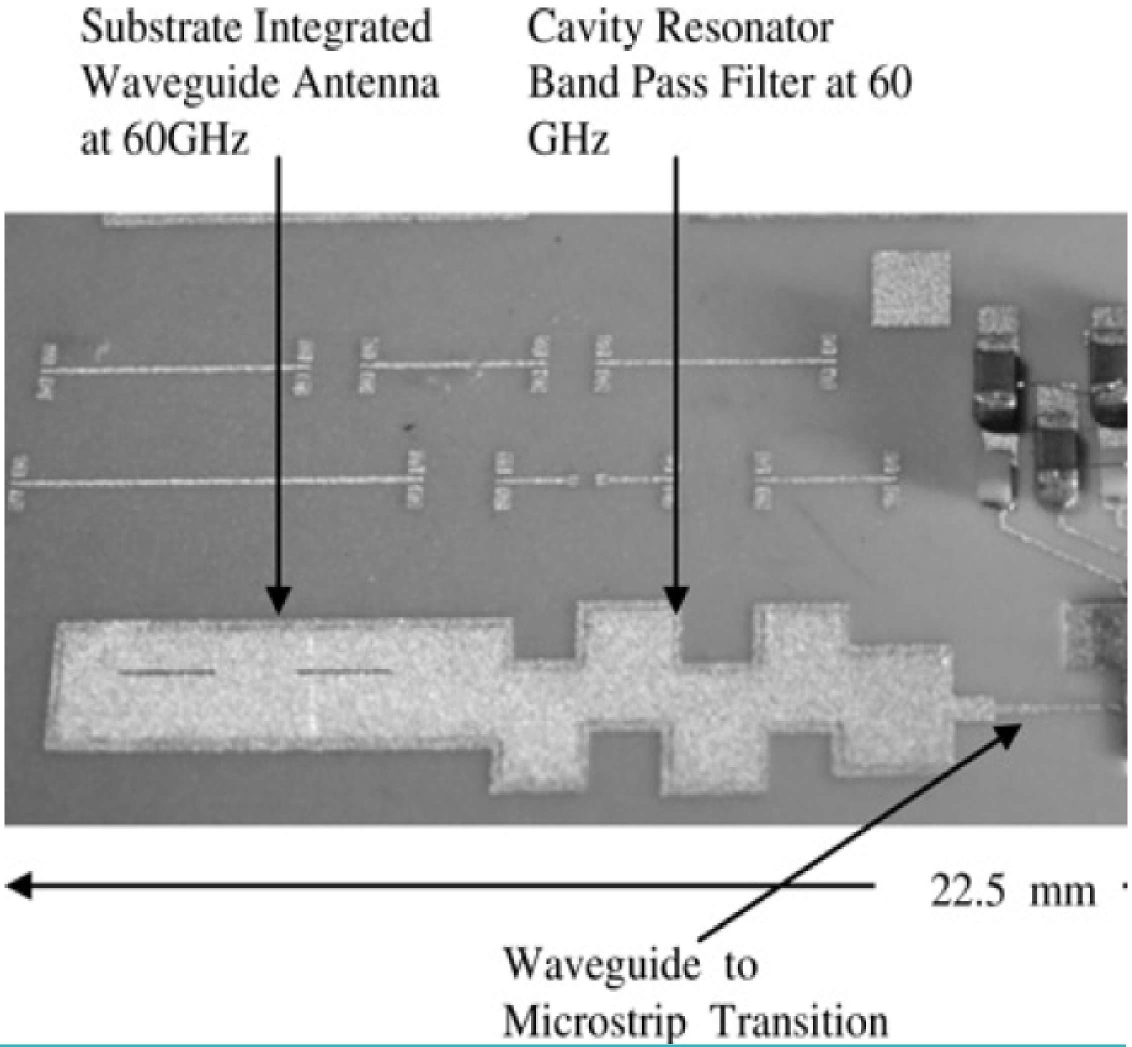
✍ Tuneable RETINA filters, with λg/2 resonant cavities coupled by inductive irises





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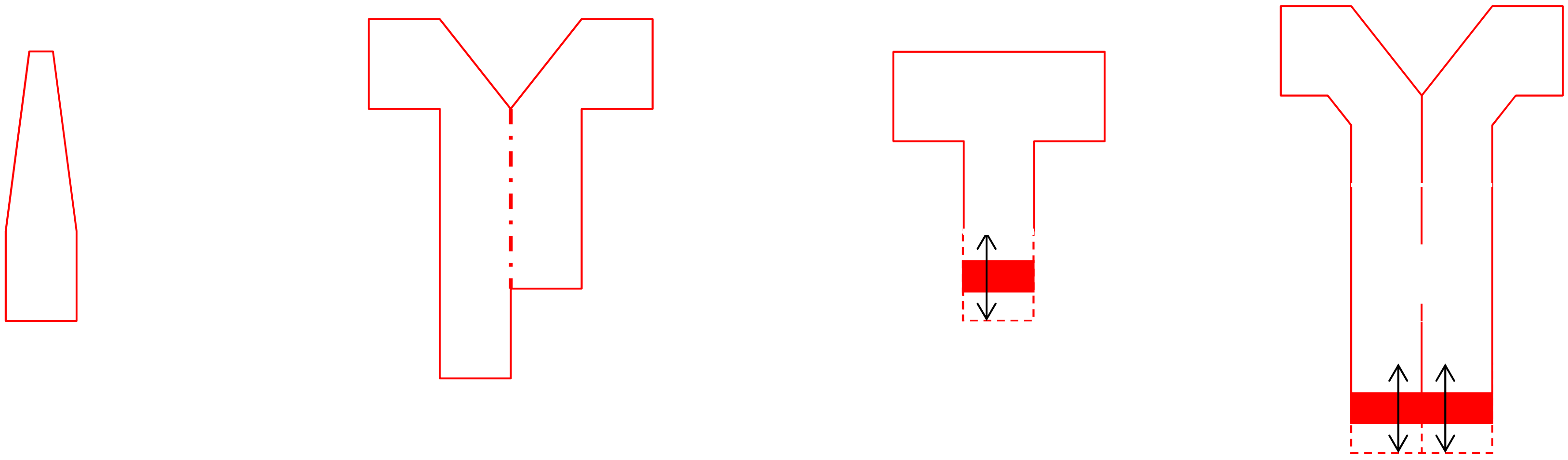
✍ Other tuneable RETINA exemplars:

- radiating tapered horn antennas
- variable power splitters
- tuneable short circuit stubs
- variable delay line



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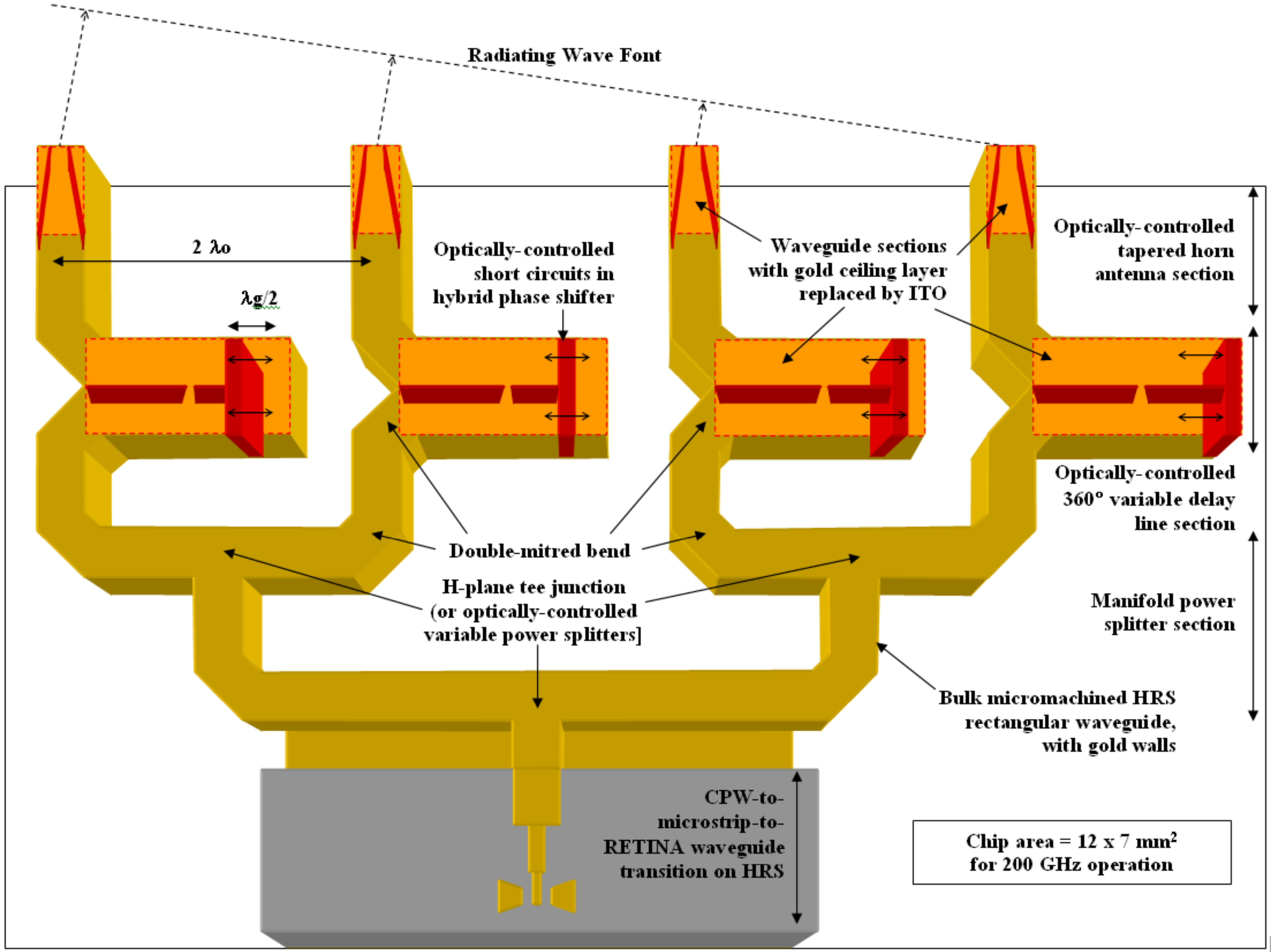
✍ Hybrid scanning phased array antenna demonstrator at 200 GHz



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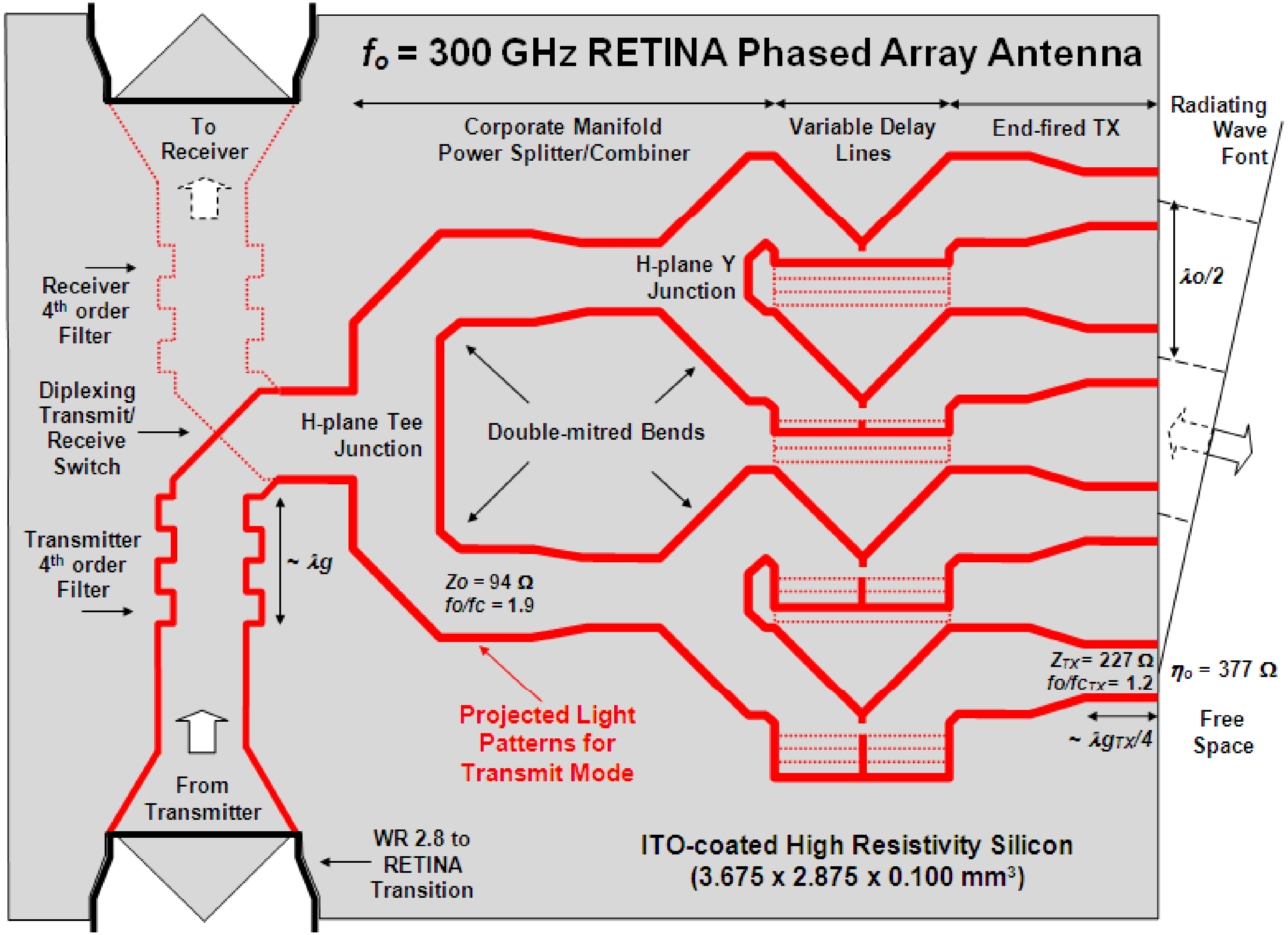
300 GHz RETINA phased array scanning antenna, with switchable transmit and receive modes, indicating calculated parameters and associated dimensions (all drawn to scale)



Light Technologies

✍ **The pattern of incident light can be controlled in a number of ways**

Proximity shadow mask

- Very inefficient, with almost all incident optical power being wasted
- Non-tuneable components only
- Reasonable approach for an initial demonstration

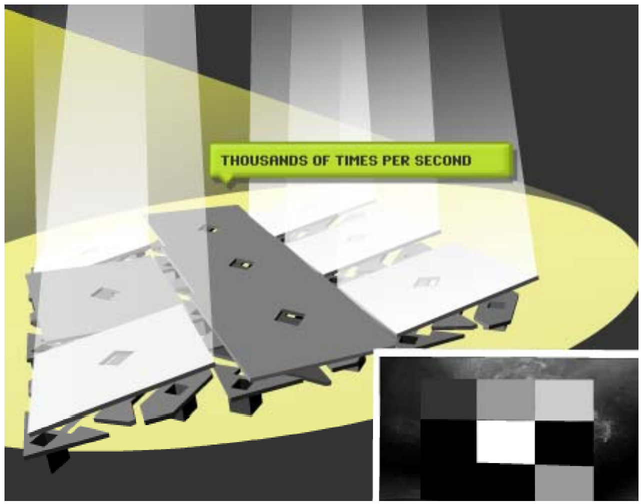
Bespoke refractive or diffractive optics

- very efficient
- non-tuneable components only

Spatial Light Modulator (SLM)

e.g. replacing the white light source in a Texas Instruments DLP® projector by a near-IR laser source:

- Versatile illuminator that could be interfaced with a PC
- Programmed using even a simple drawing package
- Power handle issues, with dumped energy
  i.e. the energy not transmitted to the substrate



Phase-modulated SLM

• 90% light utilization efficiency.

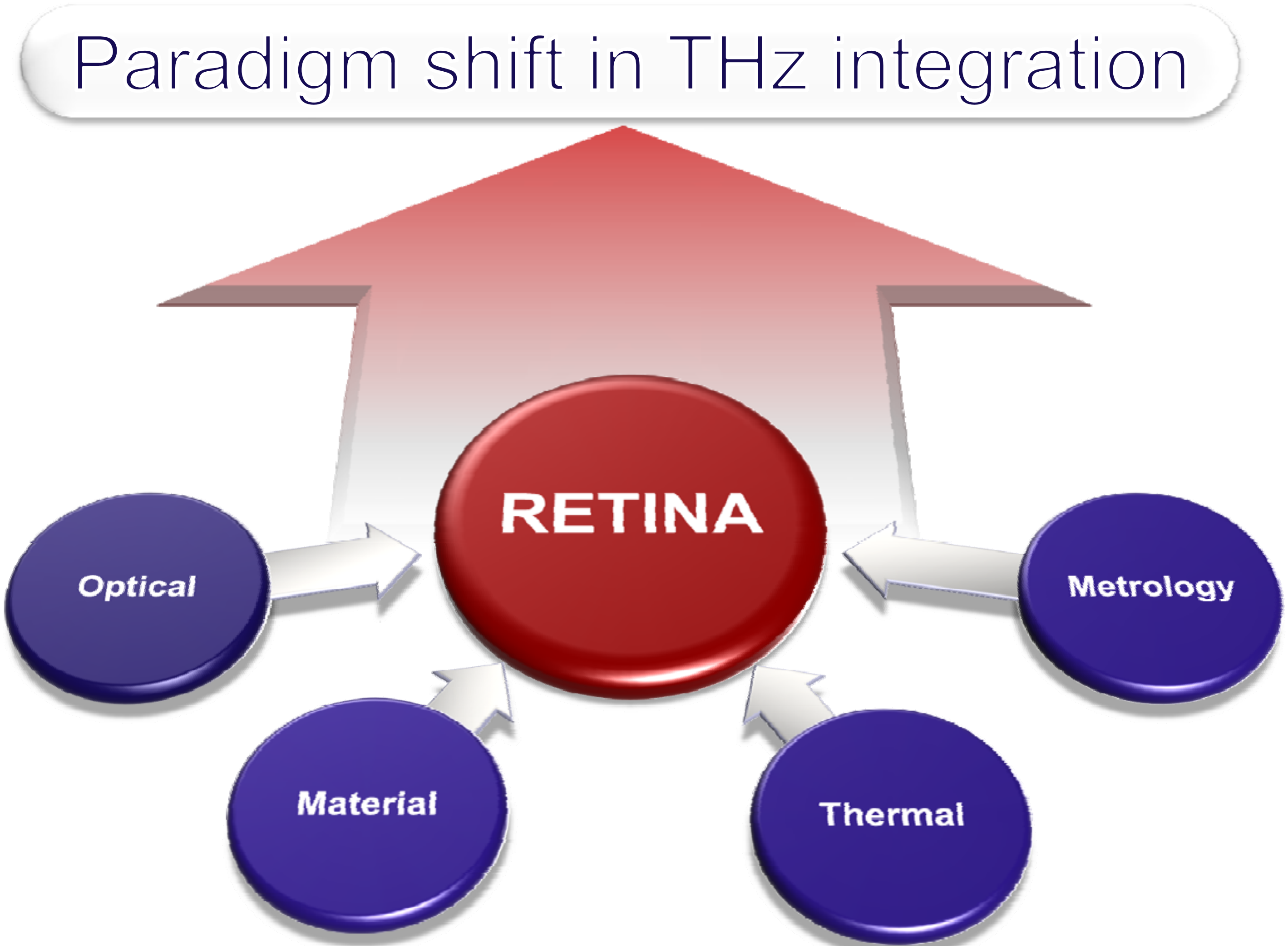
• Commercial liquid crystal on silicon (LCOS) SLMs, appear to be ideally suited for this application

Scanned focused laser

• Spot writing time for the complete pattern would have to be smaller than the electron-hole pair recombination time

• Challenging for large/complex architectures

Conclusions



✍ **RETINA can provide:**

Integration

Reconfigurability

Tunability

✍ **At the expense of:**

Increased Losses

Increased Complexity (Optics)

✍ Loss Reduction Techniques:

Bespoke transparent conductive oxide

Optimize substrate/wavelength/power

Double-sided exposure

Over-sized waveguide

Superposition of CW and pulse excitation

Acknowledgements

✍ Professor Andrew S. Holmes (Imperial College London) for his contribution to the thermal analysis

✍ UK Government's Overseas Research Students (ORS) Awards Scheme for part-funding of this PhD research

✍ SILVACO, for their donated software and support

✍ Professor Maurizio Bozzi and the Workshop organisers

Thank You !