Modeling Issues for CMOS RF ICs

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Agenda

- Motivation
- Integrated Inductor
- Co-Planar Waveguide
- Conclusion

Motivation

- Commercial CMOS technology, silicon based, has evolved throughout the years to now become the best alternative for many wireless applications.
- It's a mature, well understood, and inexpensive technology.
- MOS Transistors have been built to operate at frequencies of hundreds of GHz.
- With these, complex ICs have been designed and manufactured, allowing for more on-chip functions than ever before.
- This trend will continue for many years, even though we are reaching the physical limits of integration.

2018 IEEE Custom Integrated Circuit Conference (CICC), 8-11 April 2018, San Diego, CA, USA, pp. 1-8.
DOI: 10.1109/CICC.2018.8357054

CMOS Terahertz Receivers

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***Abstract*—Recent advances of devices and circuits have made CMOS (Complementary Metal Oxide Semiconductor) integrated circuits technology an alternative for realizing capable and affordable THz systems. Coherent detection up to 410 GHz and incoherent detection up to 10 THz as well as an almost fully integrated receiver working from 225-280 GHz have been demonstrated using CMOS. Despite the fact that f_{max} of NMOS transistors has peaked around 320 GHz, it should be possible to coherently detect signals at frequencies beyond 1 THz and with some straightforward modification of processes, to incoherently detect signals at 40 THz in CMOS.**

Keywords—coherent; incoherent; receiver; detector; CMOS; THz; Sub-millimeter wave

scaling with the technology nodes has made generation of a local oscillator (LO) signal with a necessary amplitude for mixing operation more challenging.

B. Interconnects

Metal interconnects of CMOS technologies have a significant impact to the terahertz performance of devices and circuits. Interconnect parasitics reduce f_{max} of NMOS transistors [11]. For instance, in 45-nm SOI (Silicon On Insulator), adding metal connections to the top metal layer for making interconnection to other passive and active devices lowers f_{max} from ~400 GHz to 280 GHz [11].

2020 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT)

CMOS Platform for Terahertz

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***Abstract*— The Complementary Metal Oxide Semiconductor (CMOS) integrated circuits technology has emerged as a means for realization of capable and affordable systems that operate at 300 GHz and higher. This is bridging the Terahertz Gap and enabling everyday life applications utilizing this portion of the spectrum. Signal generation up to 1.3 THz, coherent detection up to 1.2 THz, and incoherent detection up to ~10 THz have been demonstrated using CMOS. Furthermore, a highly integrated rotational spectroscopy transceiver for electronic smelling operating up to near 300 GHz, a 30-Gbps 300-GHz QPSK transmitter for data communication with an output power of -6 dBm and an imaging array operating at 820 GHz have been demonstrated in CMOS. These along with the data in the literature suggest that the necessary terahertz electronics for everyday life applications can be affordably manufactured.**

Keywords—CMOS, terahertz, devices, circuits, systems, varactors, Schottky diodes, everyday applications

has been demonstrated [9]. These limit the maximum frequency for linear amplification using transistors in CMOS to ~300 GHz or less [9]. Additionally, the decrease of supply voltage with the technology scaling is making generation of a sufficient power level in amplifiers and local oscillators (LO's) needed for mixing operation more difficult.

Despite these limitations, it is possible to operate CMOS circuits above 300 GHz. Similar to what the terahertz community has done for many years using III-V devices and photonic crystals, the nonlinearity of components in CMOS can be utilized to accomplish this. In fact, Schottky diodes [9] with a cut-off frequency $(2\pi RC)^{-1}$ and MOS varactor diodes [9] with a dynamic cut off frequency, $f_{cd} = (2\pi R)^{-1}\,(1/C_{min}-1/C_{max})$ over 2 THz have been reported in CMOS (Fig. 1). With increasing cut-off frequencies, responsivity (output voltage/input power) of Schottky diode detectors and conversion efficiency of varactor frequency multipliers and mixers are improved at a given operating frequency. Increasing cut-off frequencies also

See also: "Opening Terahertz for Everyday Applications", K.O. Kenneth et al., IEEE Communications Magazine, August 2019, pp. 70-76. DOI: 10.1109/MCOM.2019.1800909

CONACYT

Tokyo Tech News
https://www.titech.ac.jp/english/news/2021/048934.html

Pushed to the Limit: A CMOS-based transceiver for beyond 5G applications at 300 GHz

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Published: February 5, 2021

Scientists at Tokyo Institute of Technology and NTT Corporation develop a novel CMOS-based transceiver for wireless communications at the 300 GHz band, enabling future beyond-5G applications. Their design addresses the challenges of operating CMOS technology at its practical limit and represents the first wideband CMOS phased-array system to operate at such elevated frequencies.

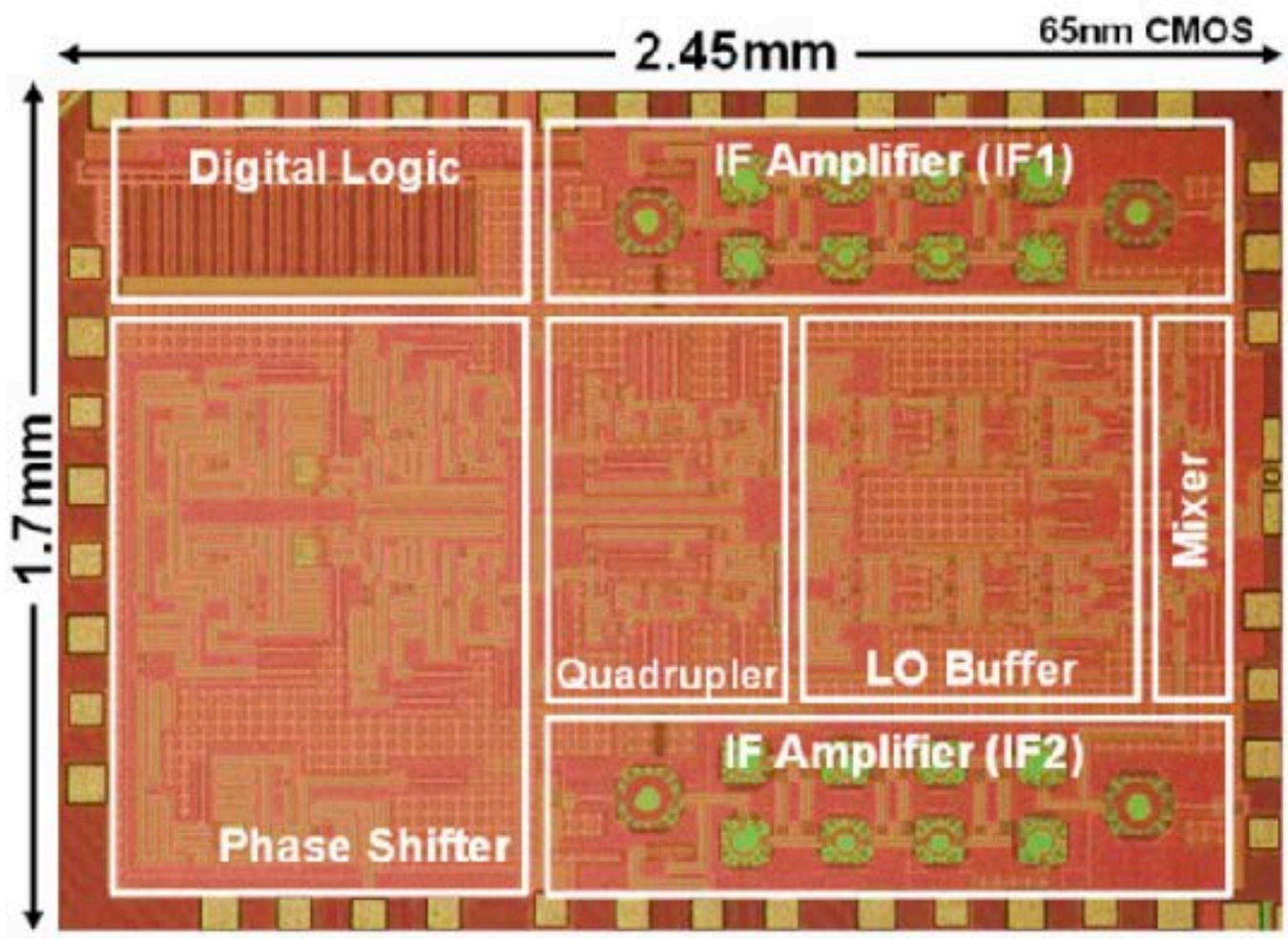
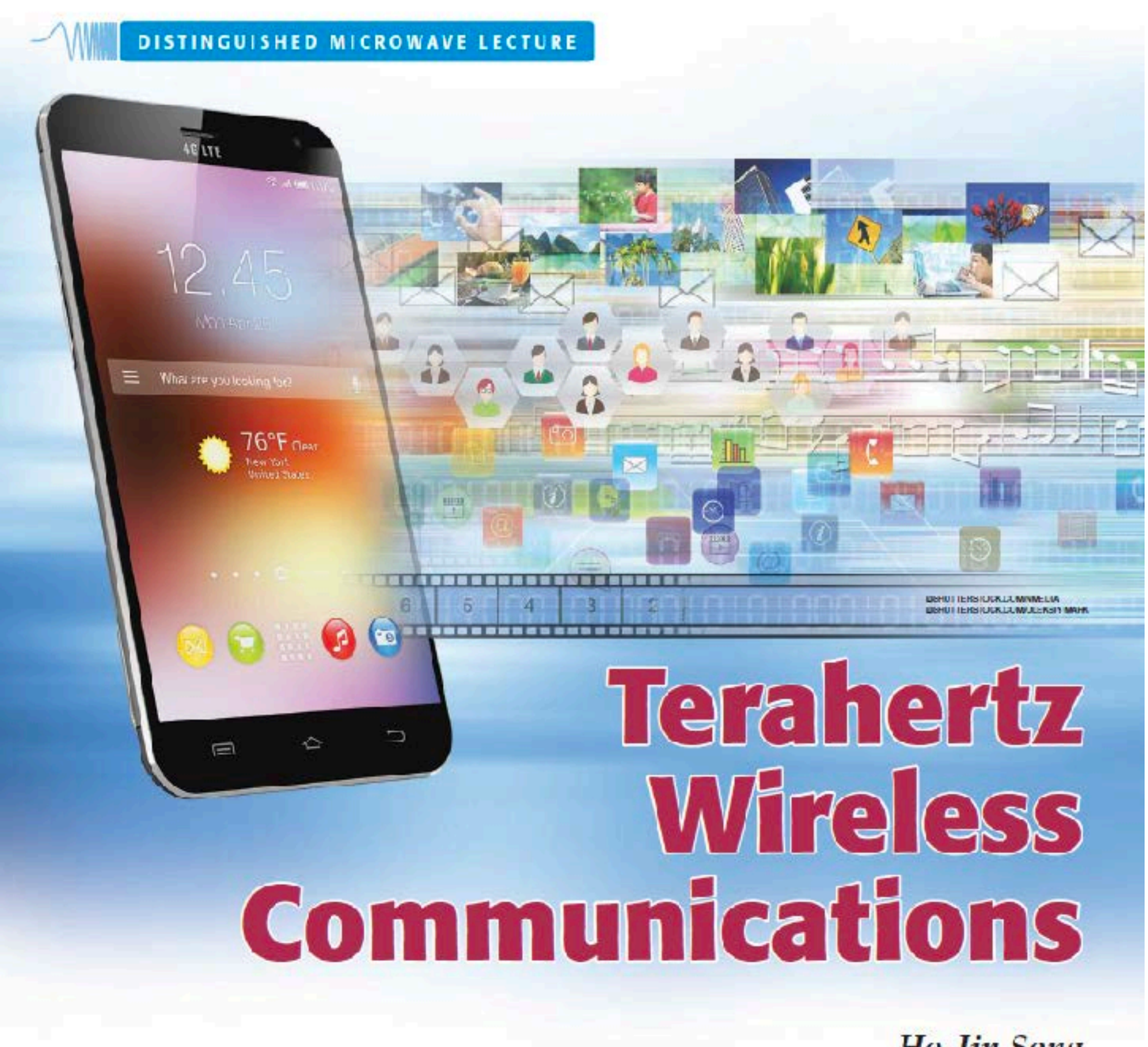


Figure 1. Chip micrograph of 300 GHz-band phased-array transceiver implemented by 65 nm CMOS



Ho-Jin Song

Nowadays, it is hard to imagine daily life without connecting to cellular communications or wireless local area networks. People are not just access-

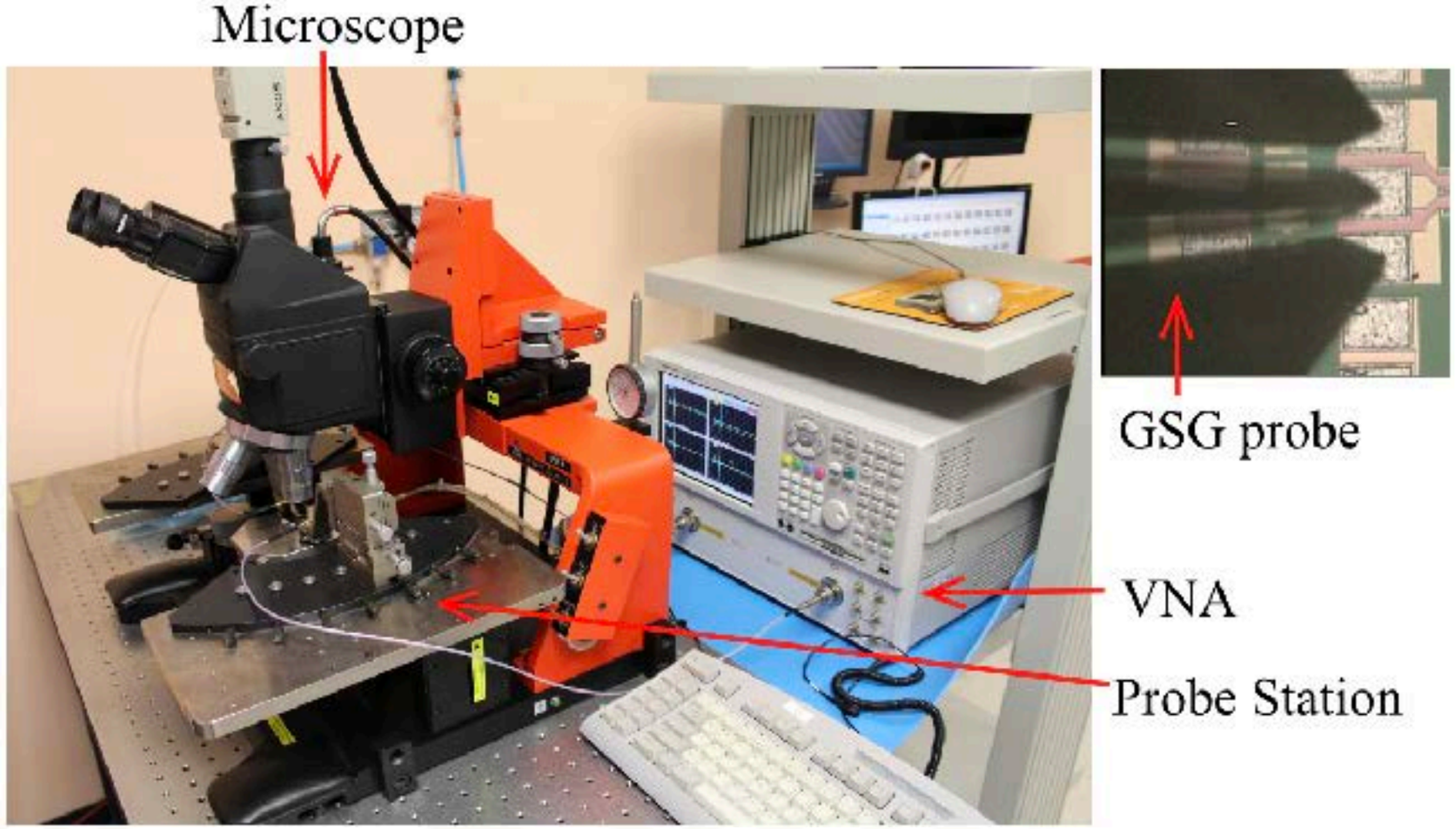
cations systems rely primarily on massive signal processing for orthogonal frequency division multiplexing and channel estimation/calibration, which has result ed in dramatically enhanced spectral efficiency and

"Terahertz Wireless Communications", H.J. Song, IEEE Microwave Magazine, Vol. 22, No. 5, May 2021, pp. 88-99. DOI: 10.1109/MMM.2021.3056935

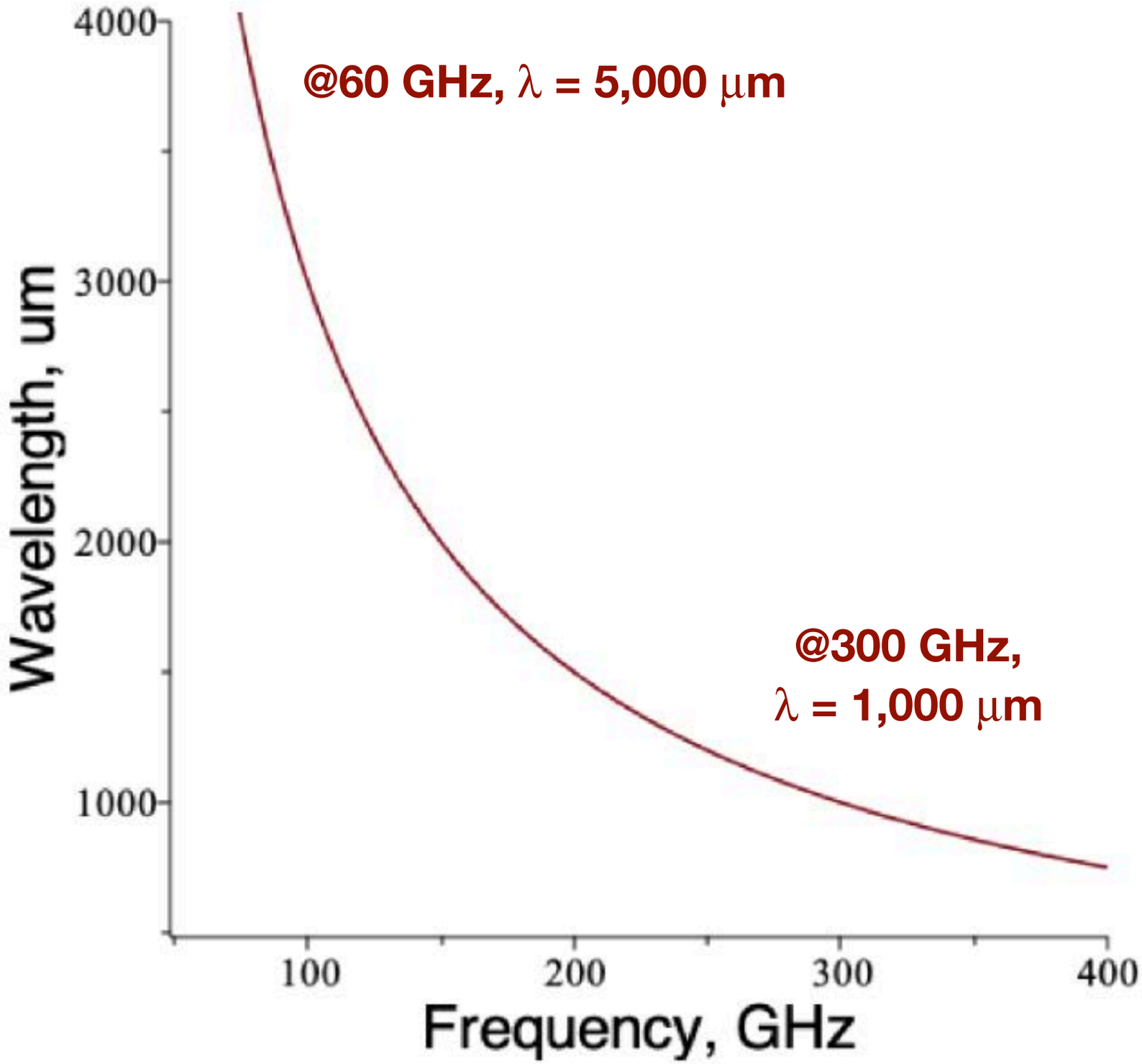
- But CMOS ICs are not only made of transistors!
- To connect these, interconnect lines are necessary.
- To reach the external world, also.
- To implement filters, capacitors and inductors are needed.
- To convert voltages to currents, resistors are used.
- All these passive devices play an important role in circuit structure.
- In fact, in a complex IC, we might find hundreds of thousands of these.
- They all have an influence on the overall behavior of the circuit.
- Hence, they have to be studied, modeled, and characterized.

- For the last three decades, we have dedicated our research efforts to the modeling, measurement and characterization of active and passive devices used for wireless communications, mostly CMOS.
- But our work also involves HF effects on PCBs, antennas, and antenna arrays for communications and energy harvesting.
- Here we present just two aspects of the work needed in this continuously expanding field of endeavor.

- Measurements were performed using a VNA.
- The system was previously calibrated using an external LRRM routine.
- All measurements were de-embedded following a three step method.
- The frequency span used for these studies went from 10 MHz to 60 GHz.

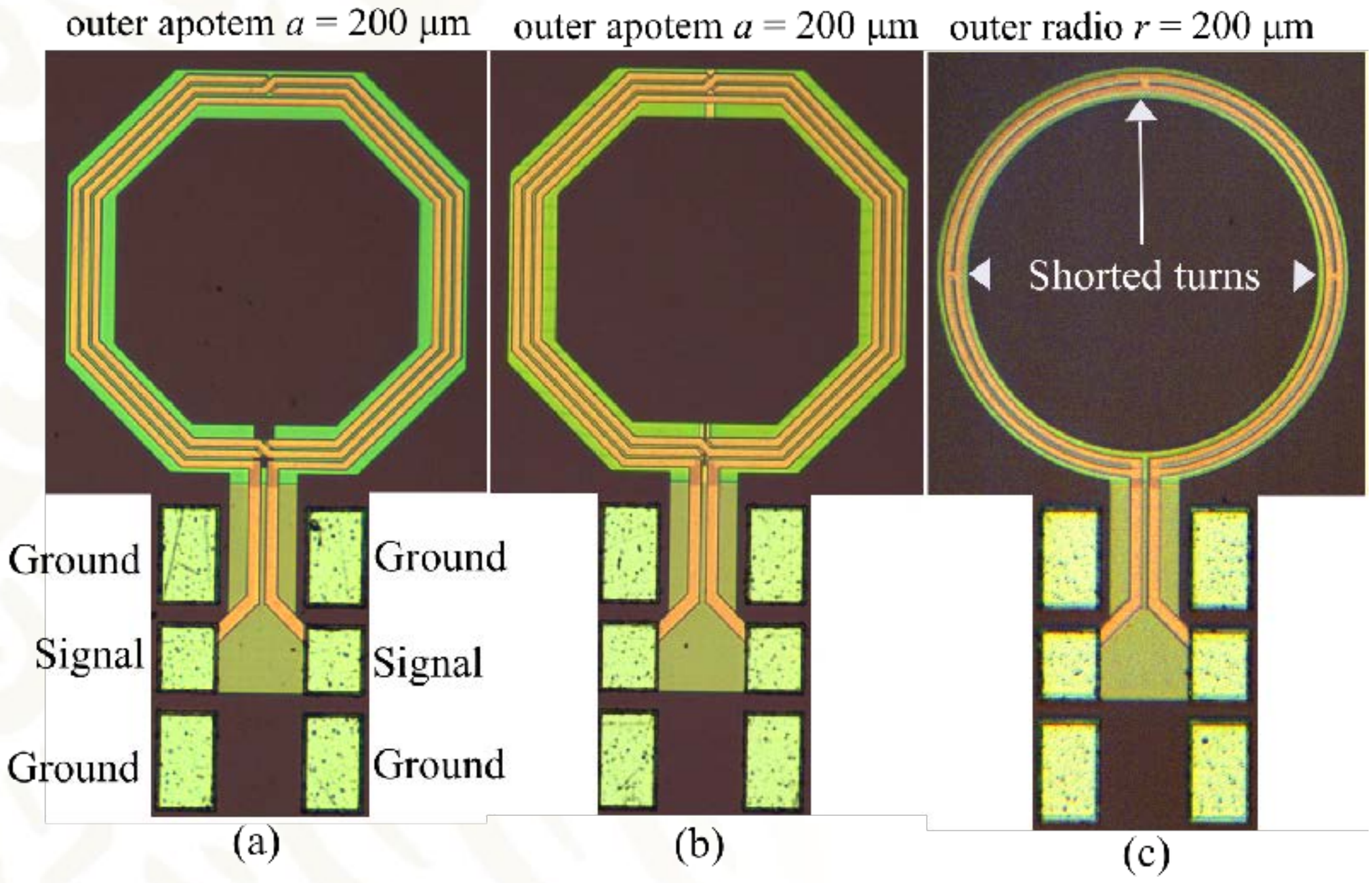


Quasi Static or NQS?

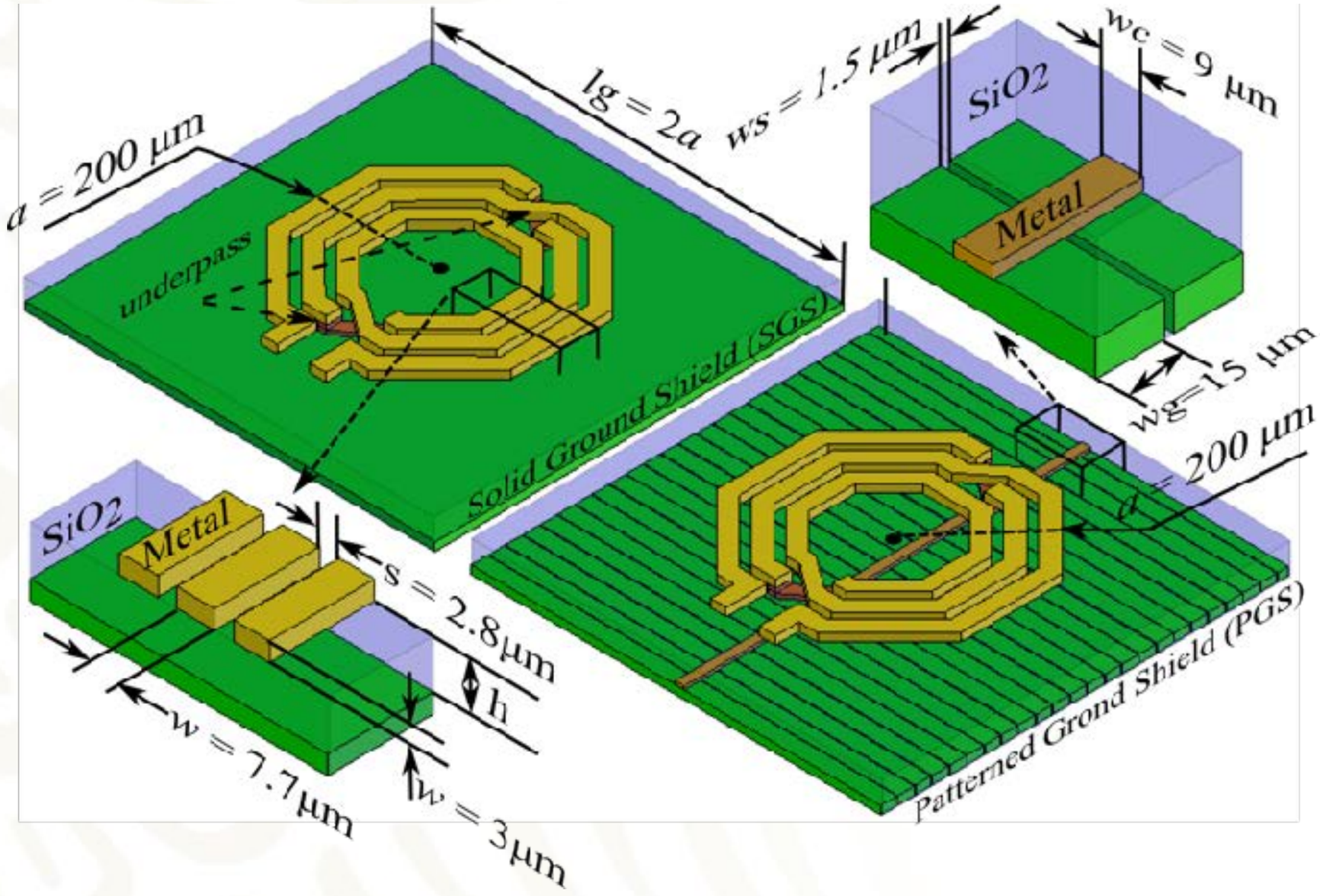


Integrated Inductor

- Inductors are probably the most important passive devices used in radio frequency ICs.
- An important figure of merit for inductors is the Quality Factor (Q).
- The value of Q strongly depends on the losses associated with eddy-currents on the ground path.
- To reduce these losses, ground shields are used underneath the inductors.
- These can be solid (SGS) or patterned (PGS).
- Shields can be built with metal, polysilicon, or low resistivity buried layers.
- A variety of inductors, from IMEC, were available for this study.

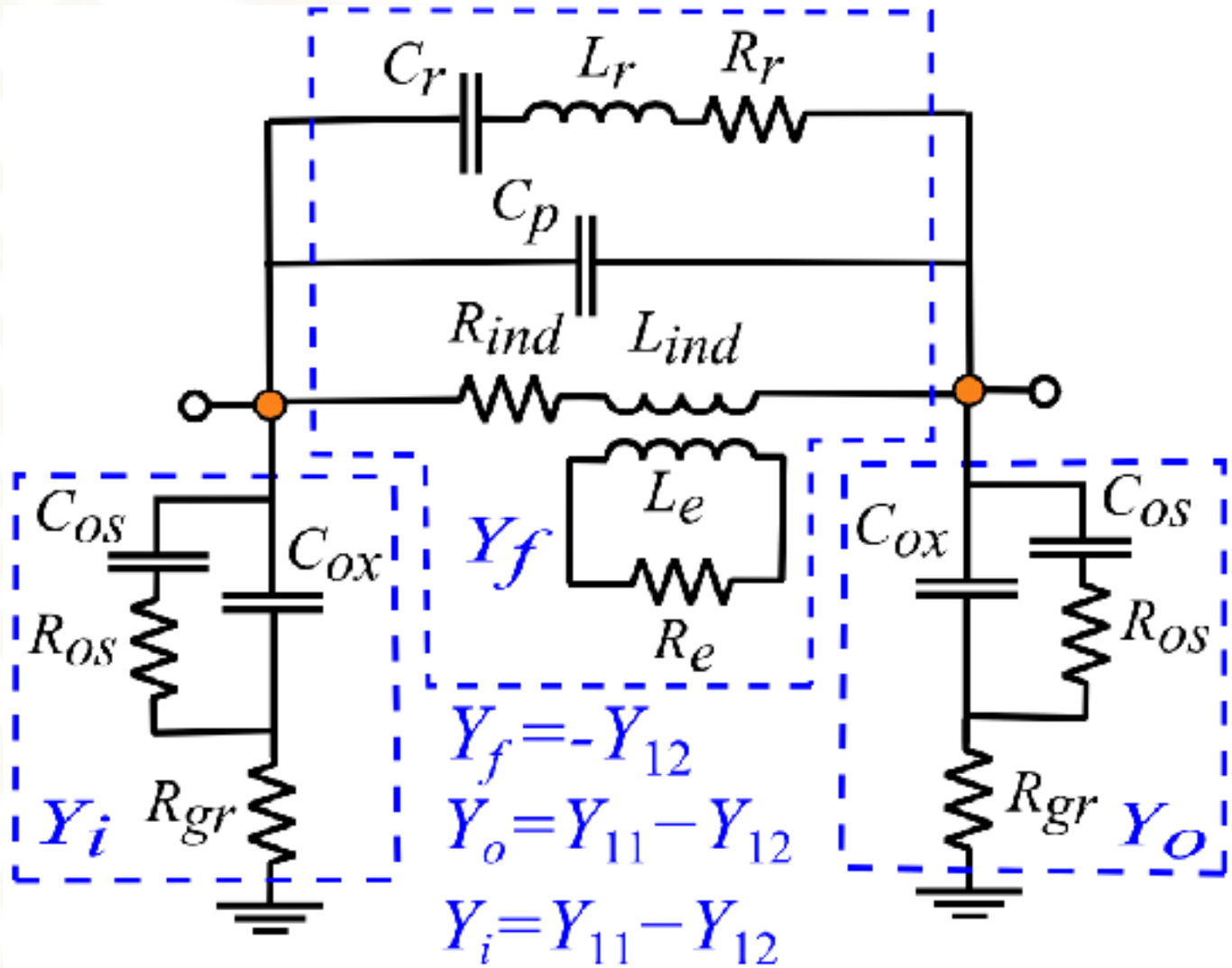


Micrograph of some of the fabricated inductors

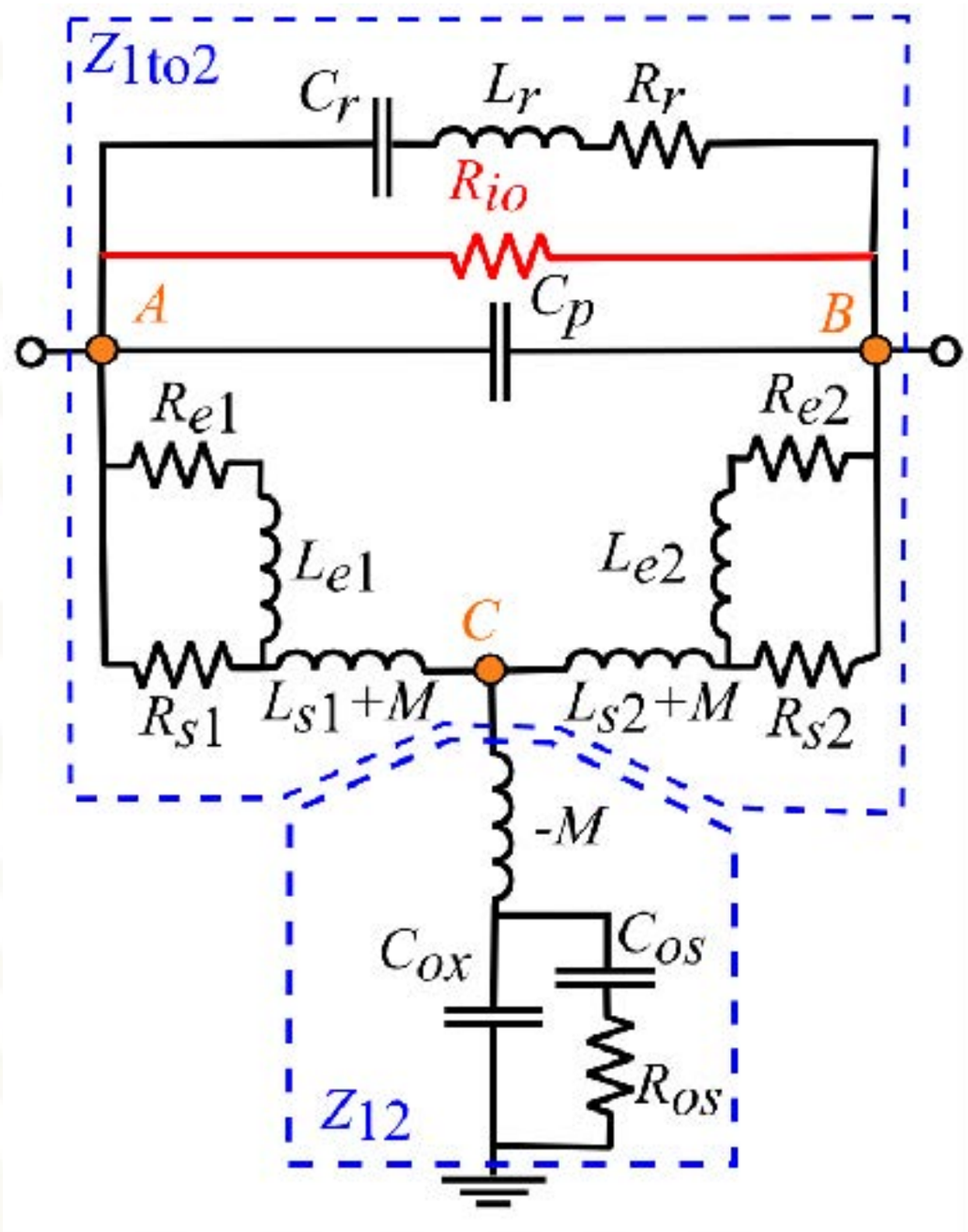


Schematic showing SGS and PGS

- The first attempt at having integrated inductors probably dates back to 1979: R.F. Soohoo, “Magnetic Thin Film Inductors for Integrated Circuit Application”, IEEE Transactions on Magnetics, Vol. MAG-15, No. 6, November 1979, pp. 1803-1805. DOI: 10.1109/TMAG.1979.1060499
- But practical inductors on ICs became common only in the late 1990s.
- Many models have been presented through the years, always changing as frequency of operation increases.
- Most are based on π and T equivalent circuit representations.



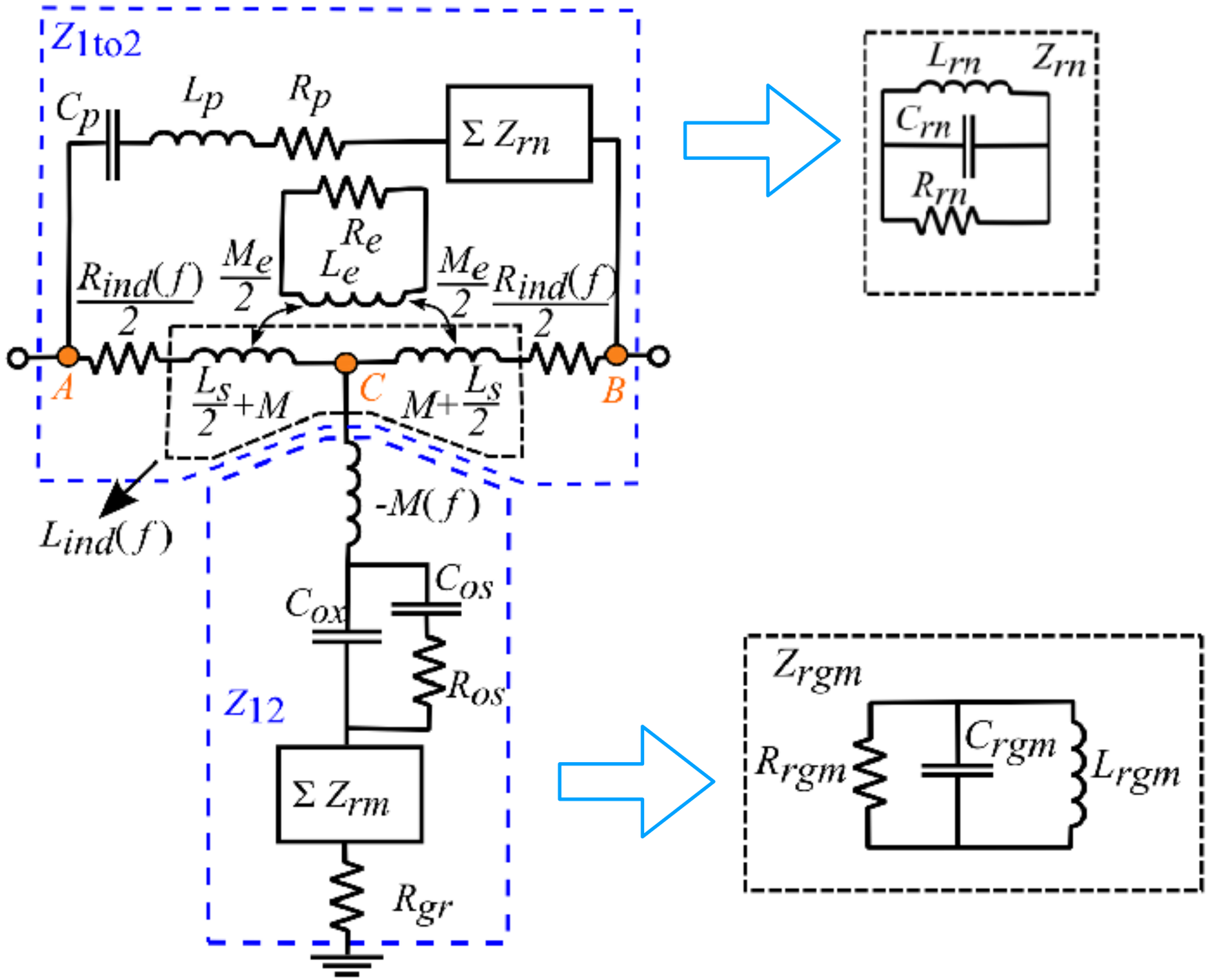
Traditional π Model



Traditional T Model

- For this work, we have adapted a traditional T model in order to represent the behavior of inductors up to 60 GHz: J. Valdés, R. Torres, R. Murphy, G. Álvarez, "Modeling Ground-Shielded Integrated Inductors Incorporating Frequency-Dependent Effects and Considering Multiple Resonances", IEEE Transactions on Microwave Theory and Techniques, Vol. 67, No. 4, April 2019, pp. 1370-1378. DOI: 10.1109/TMTT.2019.2895579
- This model provides very good correlation with experimental data.

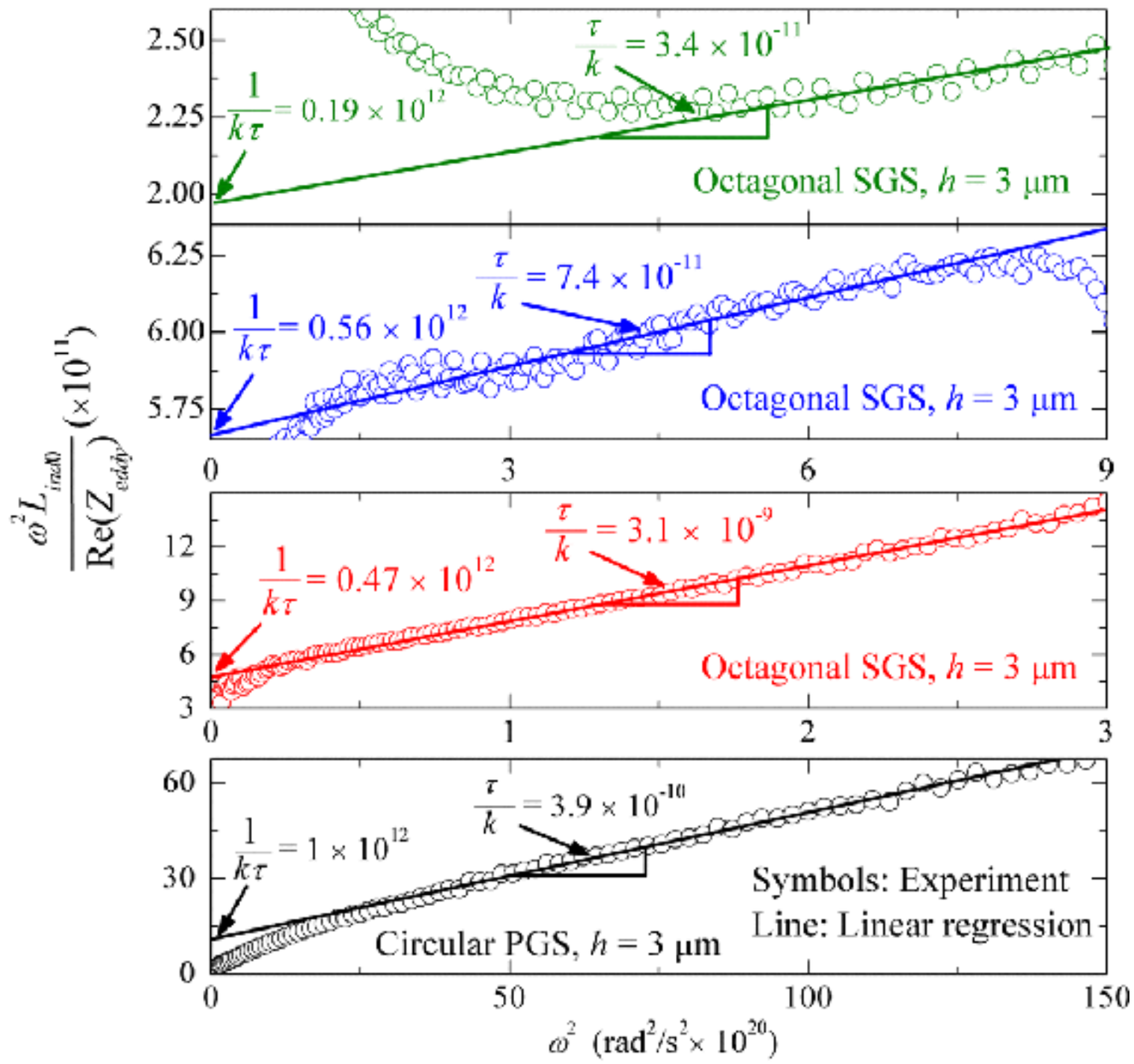
Proposed Model



- The values for all the components of the model were obtained from experimental data by defining linear relations in terms of frequency.
- A detailed description of the methodology is presented in the article in reference.
- For instance, if:

$$\frac{\omega^2 L_{ind0}}{\Re\left(Z_{eddy}\right)} \approx \frac{\tau}{k}\omega^2 + \frac{1}{k\tau}$$

- The slope of a linear regression is τ/k, whereas the intercept is $(1/k\tau)$.

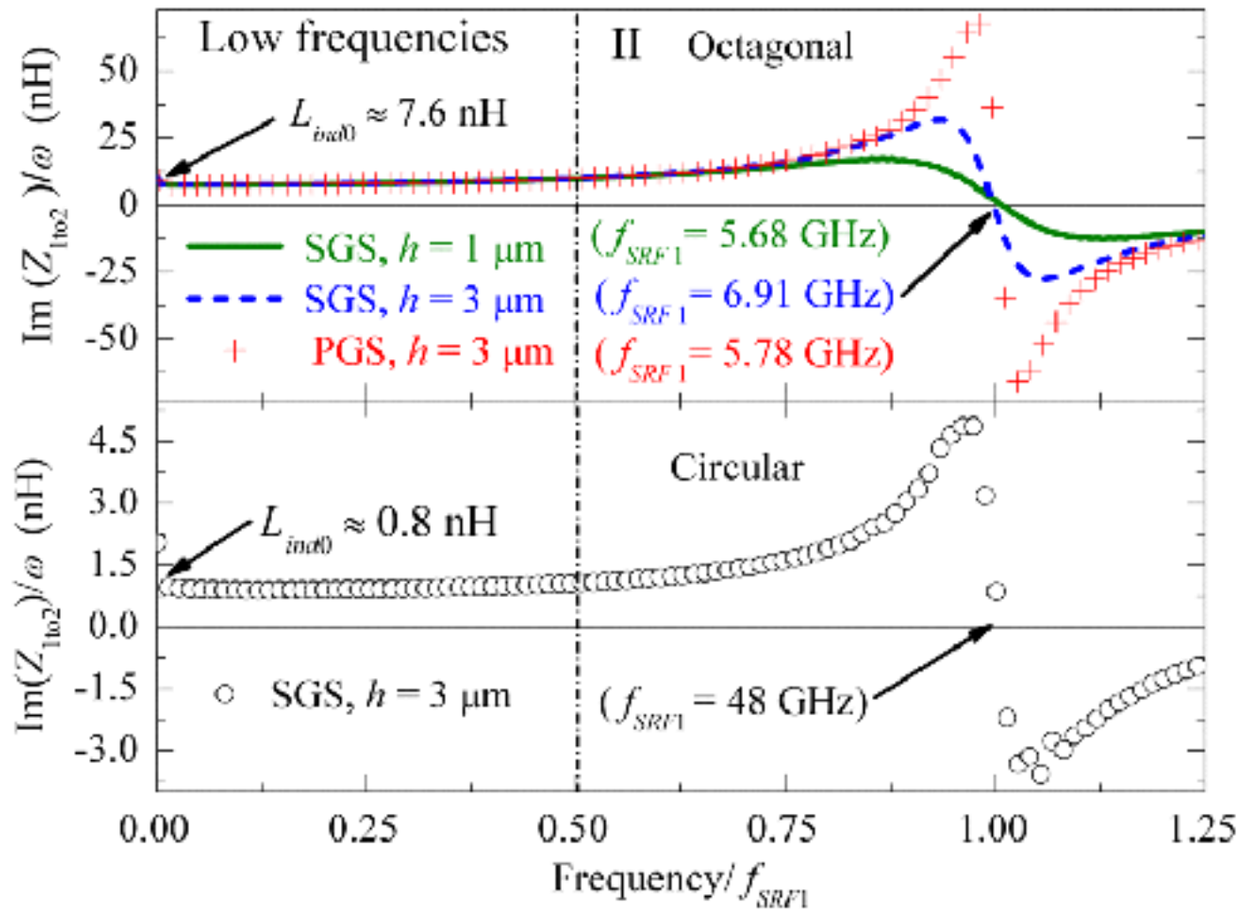

$\frac{\tau}{k} = 3.4 \times 10^{-11}$
$\frac{1}{k\tau} = 0.19 \times 10^{12}$
Octagonal SGS, $h = 3$ μm
$\frac{\tau}{k} = 7.4 \times 10^{-11}$
$\frac{1}{k\tau} = 0.56 \times 10^{12}$
Octagonal SGS, $h = 3$ μm
$\frac{\tau}{k} = 3.1 \times 10^{-9}$
$\frac{1}{k\tau} = 0.47 \times 10^{12}$
Octagonal SGS, $h = 3$ μm
$\frac{\tau}{k} = 3.9 \times 10^{-10}$
$\frac{1}{k\tau} = 1 \times 10^{12}$
Circular PGS, $h = 3$ μm
Symbols: Experiment
Line: Linear regression
$\frac{\omega^2 L_{inductor}}{\mathrm{Re}(Z_{eddy})} (\times 10^{11})$
ω^2 (rad^2/s^2 × 10^{20})

- **An important factor taken into consideration for the model is the frequency dependence of resistance and inductance:**

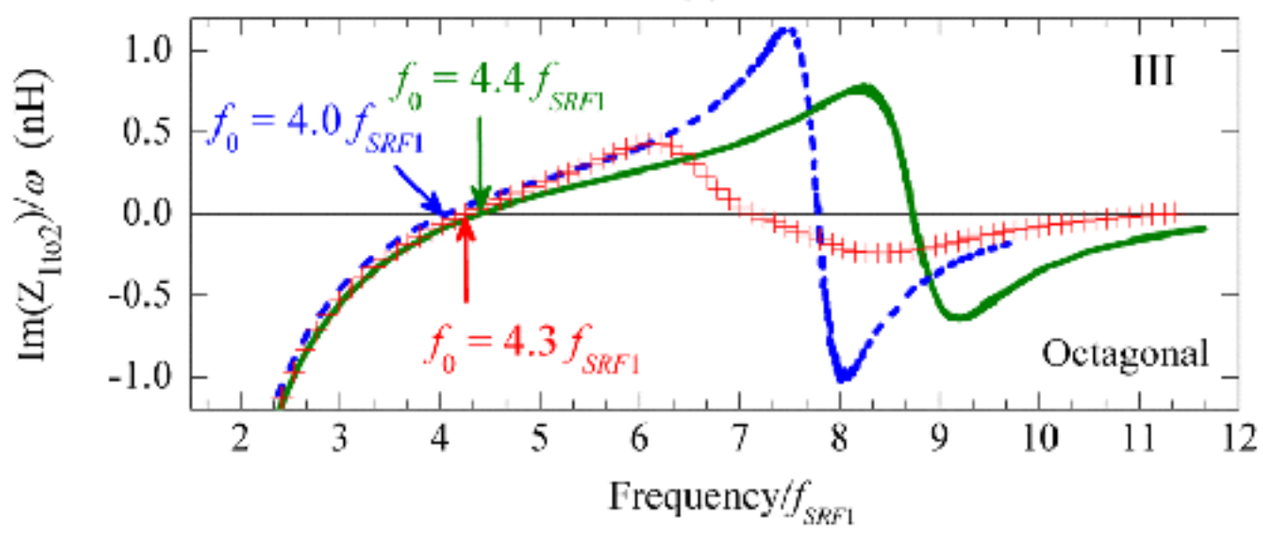
$$R_{ind} = R_{ind0} + k_s \sqrt{f}$$

$$L_{ind} = L_{\infty} + \frac{k_s}{2\pi\sqrt{f}}$$

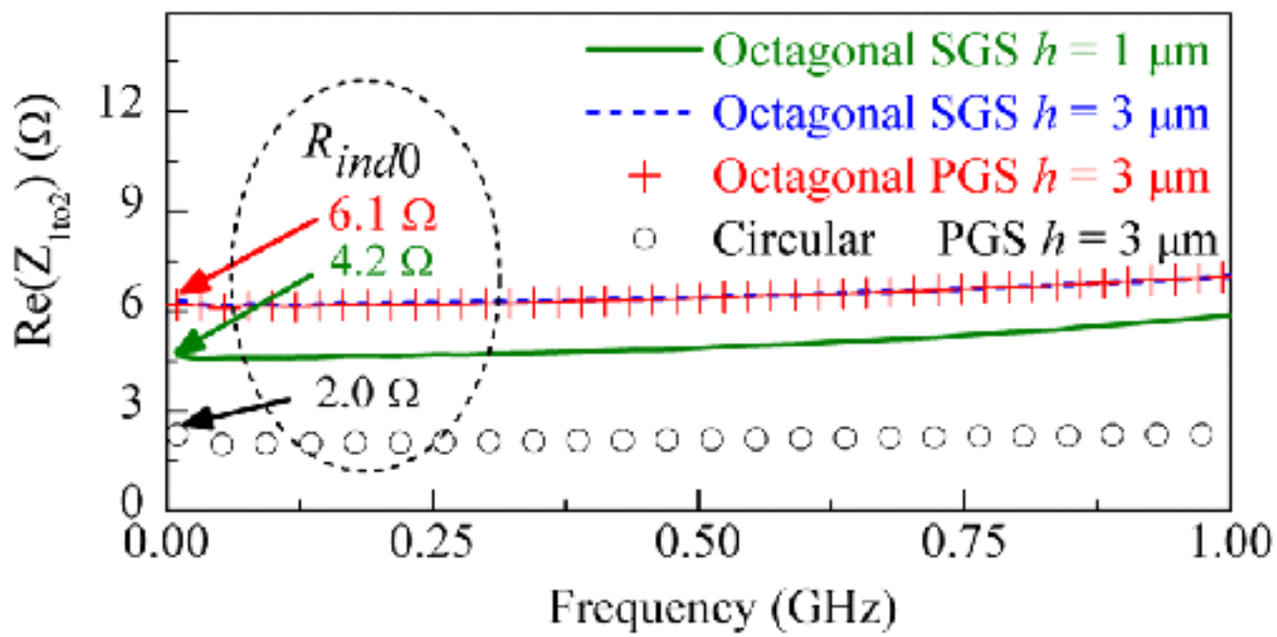
- **Thus, the skin effect is satisfactorily taken into account.**
- **Proximity effects are also considered.**


Low frequencies
II Octagonal
$L_{in(0)} \approx 7.6$ nH
SGS, $h = 1$ μm
SGS, $h = 3$ μm
PGS, $h = 3$ μm
($f_{SRF1} = 5.68$ GHz)
($f_{SRF1} = 6.91$ GHz)
($f_{SRF1} = 5.78$ GHz)
Circular
$L_{in(0)} \approx 0.8$ nH
SGS, $h = 3$ μm
($f_{SRF1} = 48$ GHz)
Im ($Z_{1\omega 2}$)/ω (nH)
Frequency/ f_{SRF1}

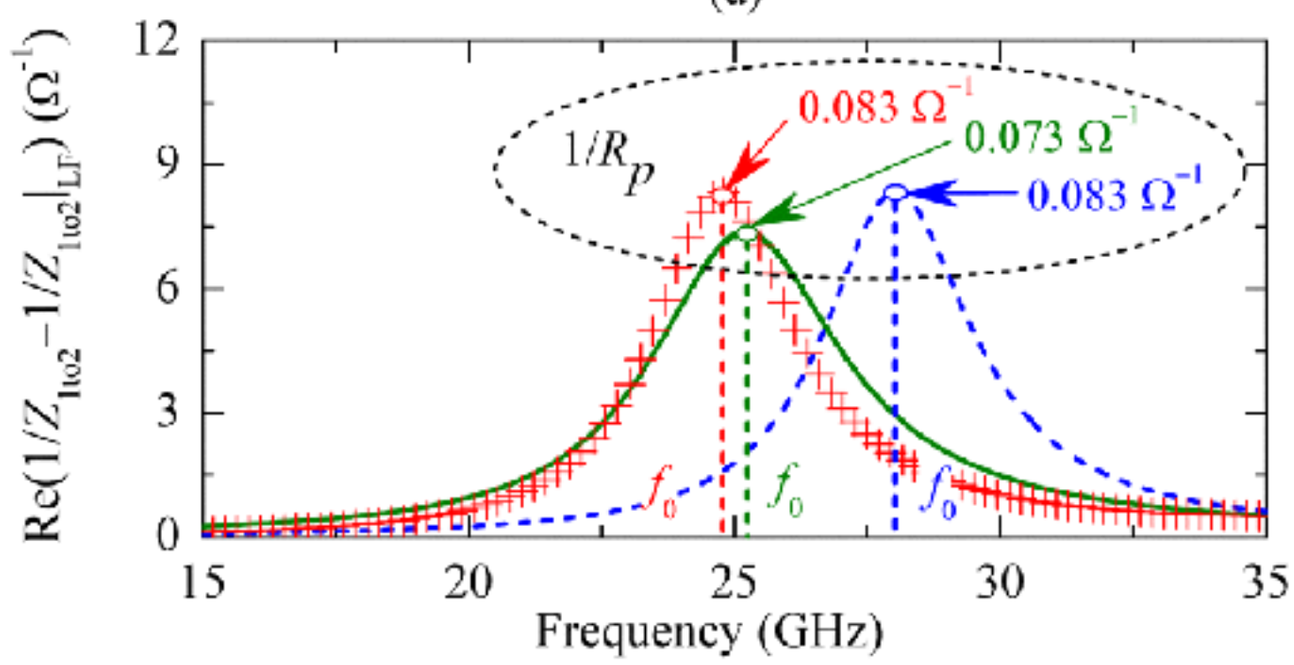
(a)


III
$f_0 = 4.4\, f_{SRF1}$
$f_0 = 4.0\, f_{SRF1}$
$f_0 = 4.3\, f_{SRF1}$
Octagonal
Im($Z_{1\omega 2}$)/ω (nH)
Frequency/f_{SRF1}

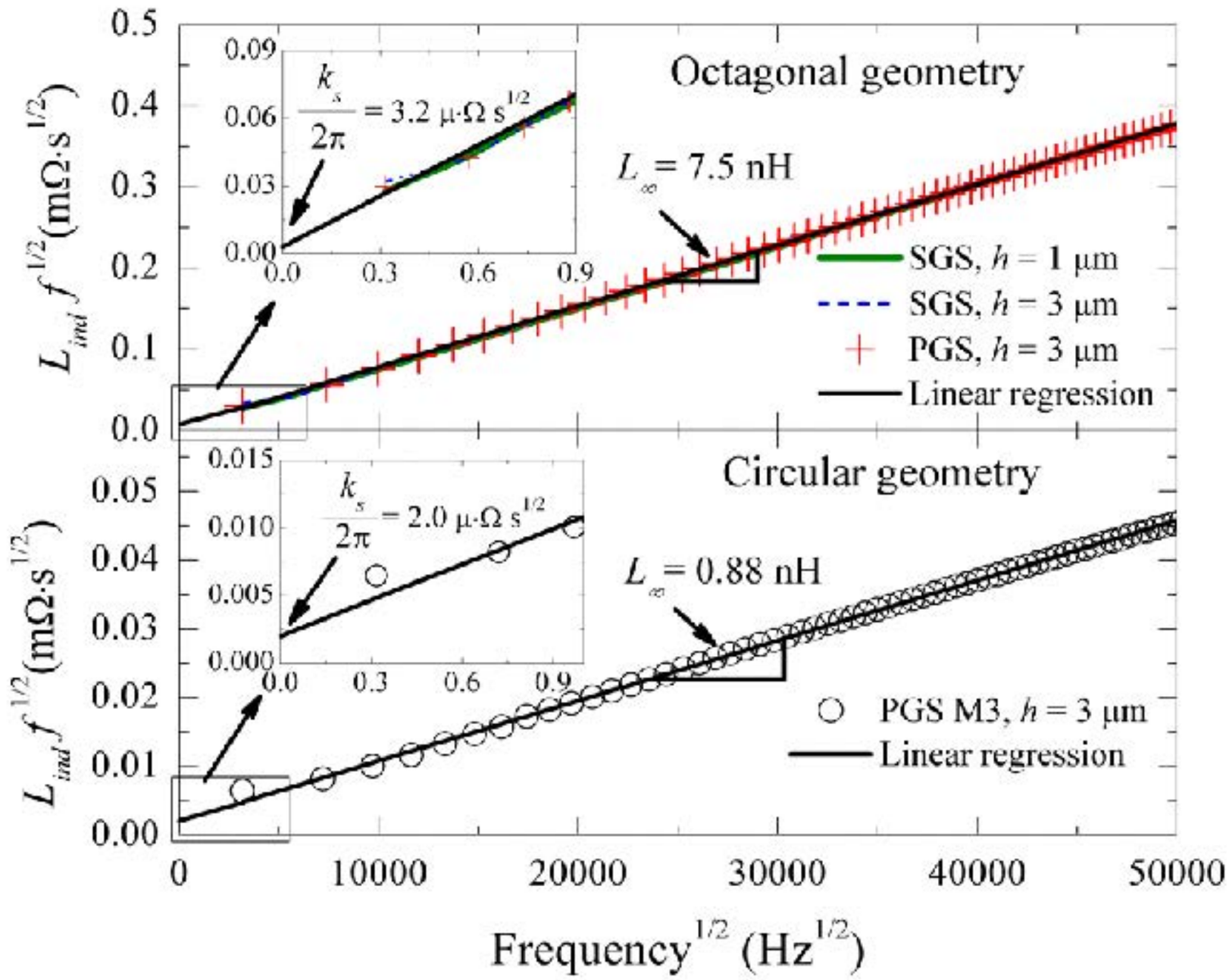
(b)

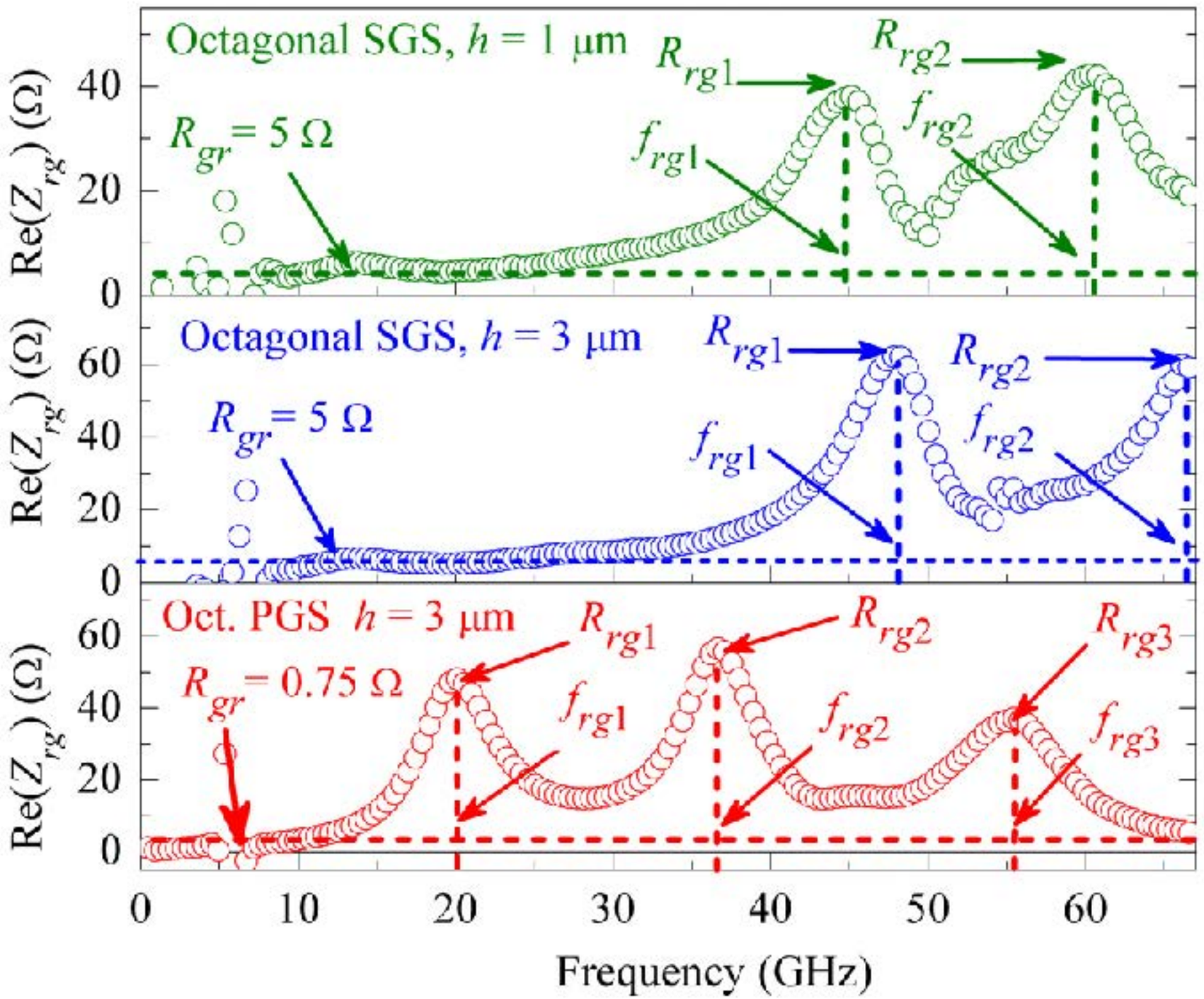

Octagonal SGS h = 1 μm
Octagonal SGS h = 3 μm
Octagonal PGS h = 3 μm
Circular PGS h = 3 μm
R_ind0
6.1 Ω
4.2 Ω
2.0 Ω
Re(Z_1to2) (Ω)
Frequency (GHz)

(a)


1/R_p
0.083 Ω^-1
0.073 Ω^-1
0.083 Ω^-1
f_0
f_0
f_0
Re(1/Z_1to2 − 1/Z_1to2|_LF) (Ω^-1)
Frequency (GHz)

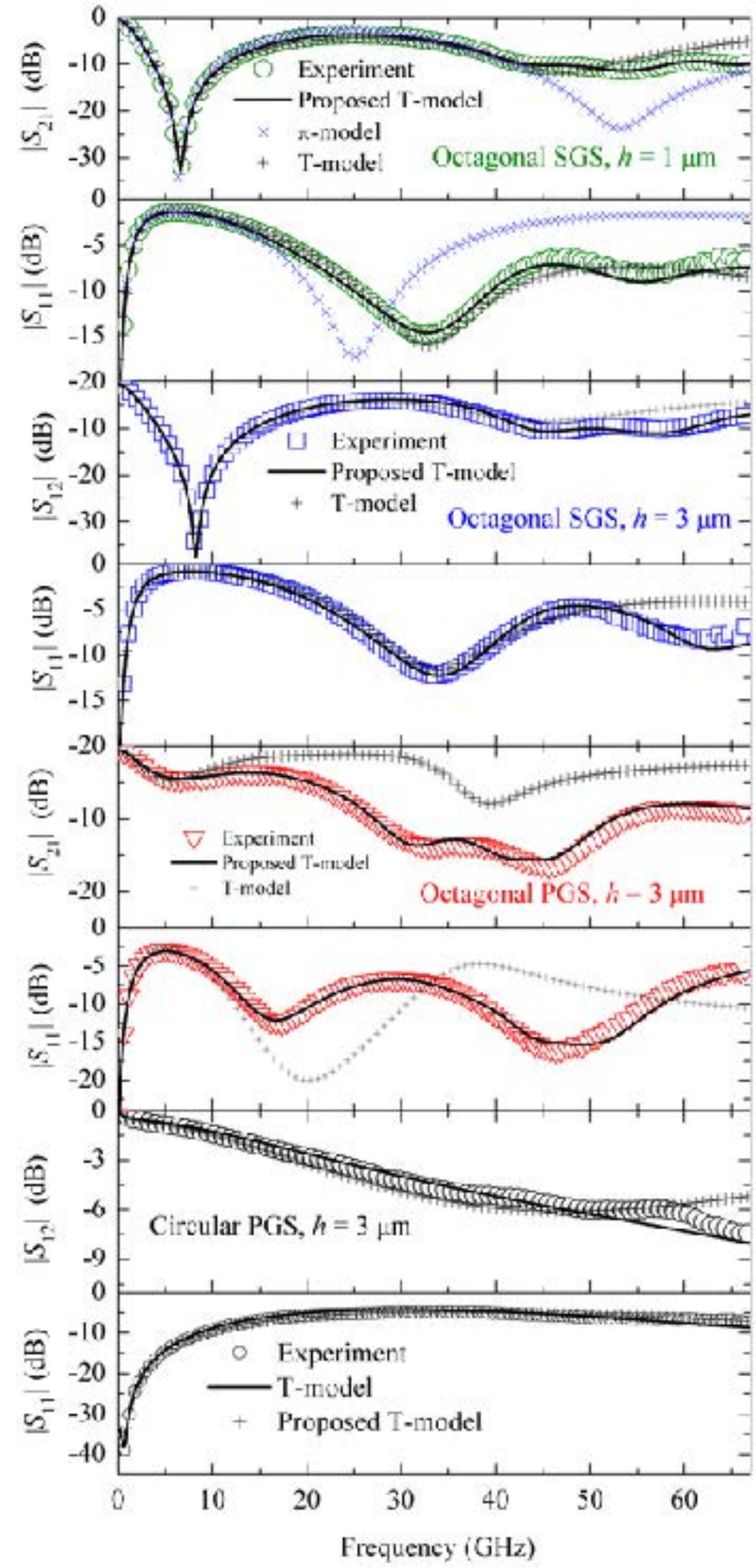
(b)

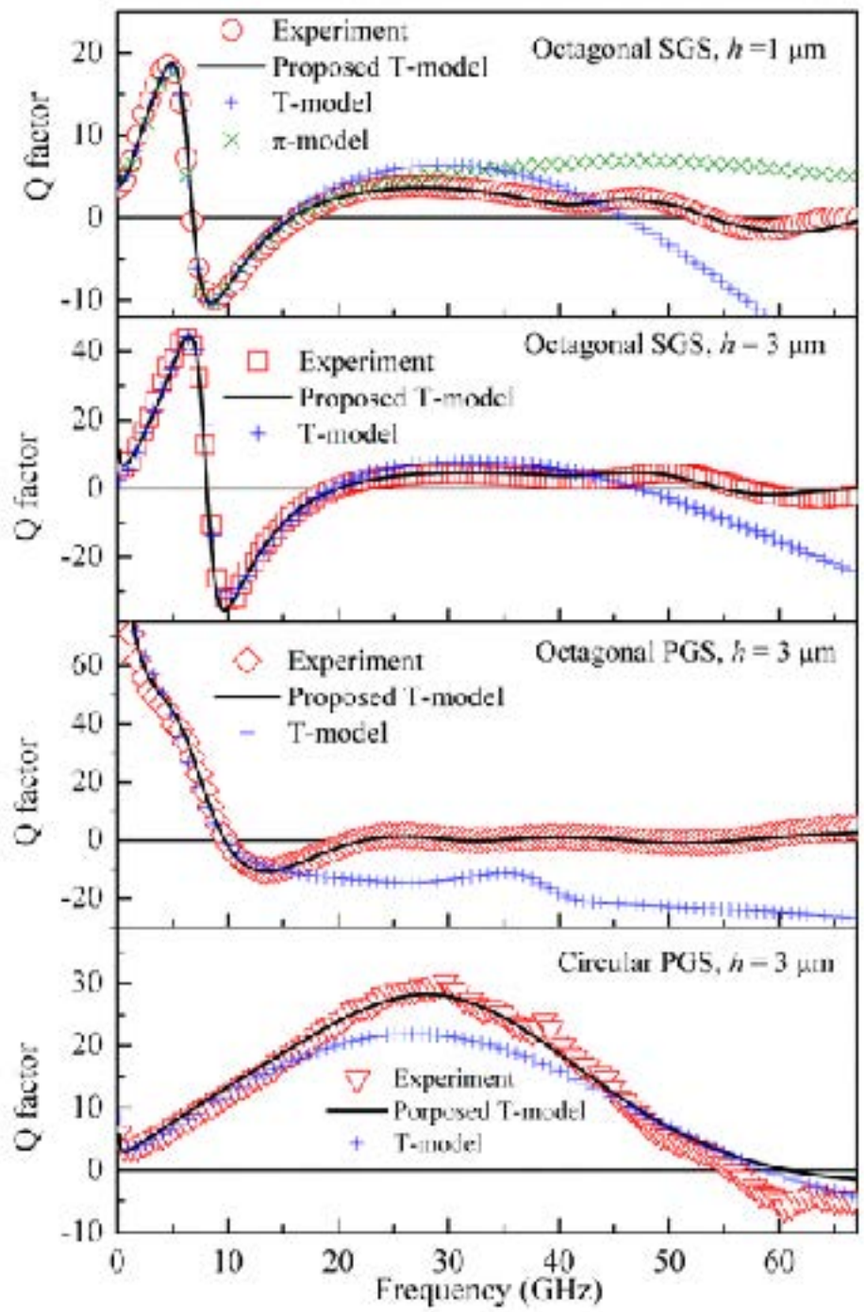

Octagonal geometry
$\frac{k_s}{2\pi} = 3.2\ \mu\cdot\Omega\ s^{1/2}$
$L_\infty = 7.5$ nH
SGS, $h = 1$ μm
SGS, $h = 3$ μm
PGS, $h = 3$ μm
Linear regression
Circular geometry
$\frac{k_s}{2\pi} = 2.0\ \mu\cdot\Omega\ s^{1/2}$
$L_\infty = 0.88$ nH
PGS M3, $h = 3$ μm
Linear regression
$L_{ind} f^{1/2}$ (mΩ·s$^{1/2}$)
Frequency$^{1/2}$ (Hz$^{1/2}$)


Octagonal SGS, h = 1 μm
R_rg1
R_rg2
f_rg1
f_rg2
R_gr = 5 Ω
Octagonal SGS, h = 3 μm
R_rg1
R_rg2
f_rg1
f_rg2
R_gr = 5 Ω
Oct. PGS h = 3 μm
R_rg1
R_rg2
R_rg3
f_rg1
f_rg2
f_rg3
R_gr = 0.75 Ω
Re(Z_rg) (Ω)
Frequency (GHz)
0
10
20
30
40
50
60

Results

- This graph shows some of the comparisons of the proposed model to experimental data.
- Also shown are the comparisons with the traditional π and T models.
- The model derived from this work shows very good correlation up to 60 GHz.




Experiment
Proposed T-model
T-model
π-model
Octagonal SGS, h =1 μm
Octagonal SGS, h = 3 μm
Octagonal PGS, h = 3 μm
Circular PGS, h = 3 μm
Q factor
Frequency (GHz)

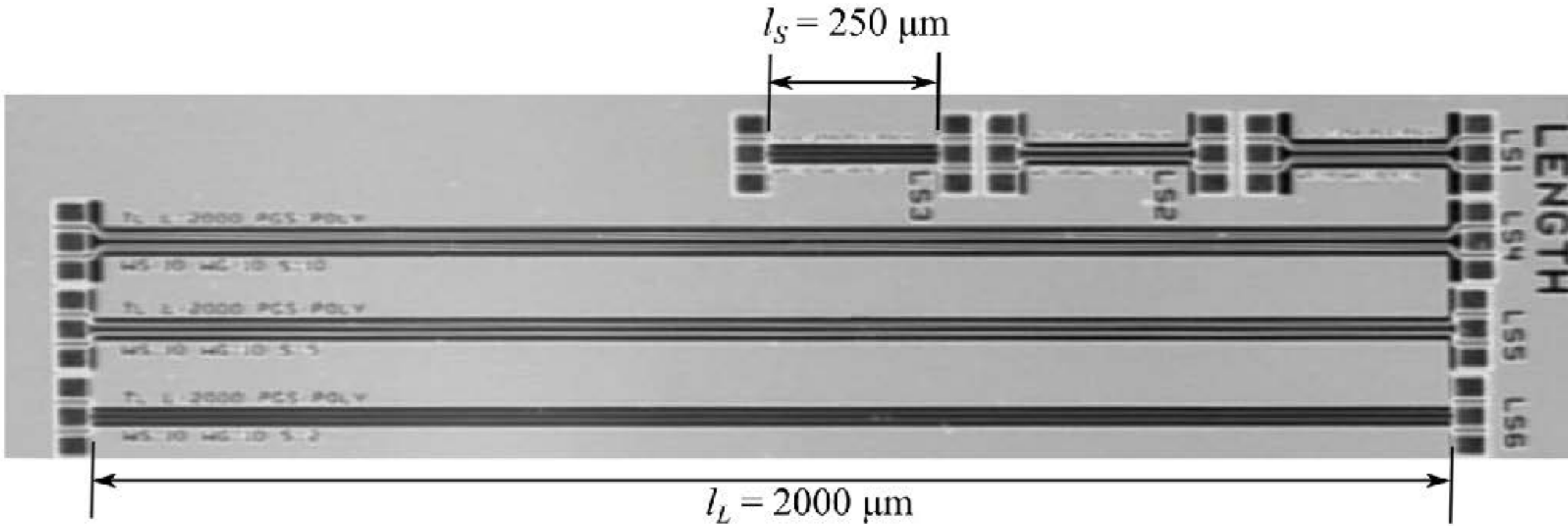
- Inductors built on a PGS show a narrower bandwidth, attributed to the reduction of eddy-current losses.
- This makes them appropriate for filter construction.
- Otherwise, there is not a clear distinction between SGS and PGS.
- The depth of the ground shield (h) influences the number of resonances; the larger h is, the higher the frequency for the additional resonances.
- The model is physically based, and does not include artificial components to attain a good correlation.
- It is probably the first one that represents different types of inductors up to 60 GHz.

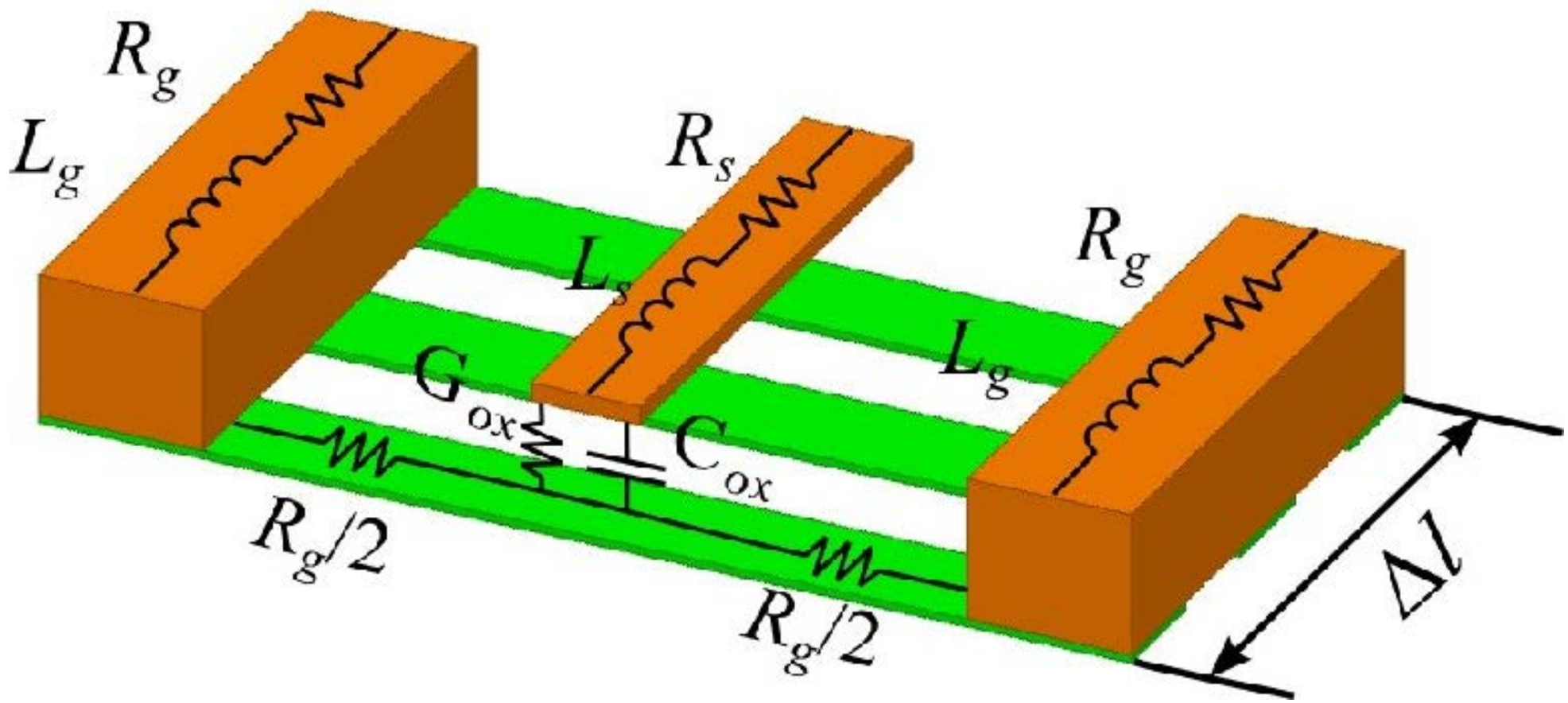
Co-Planar Waveguide

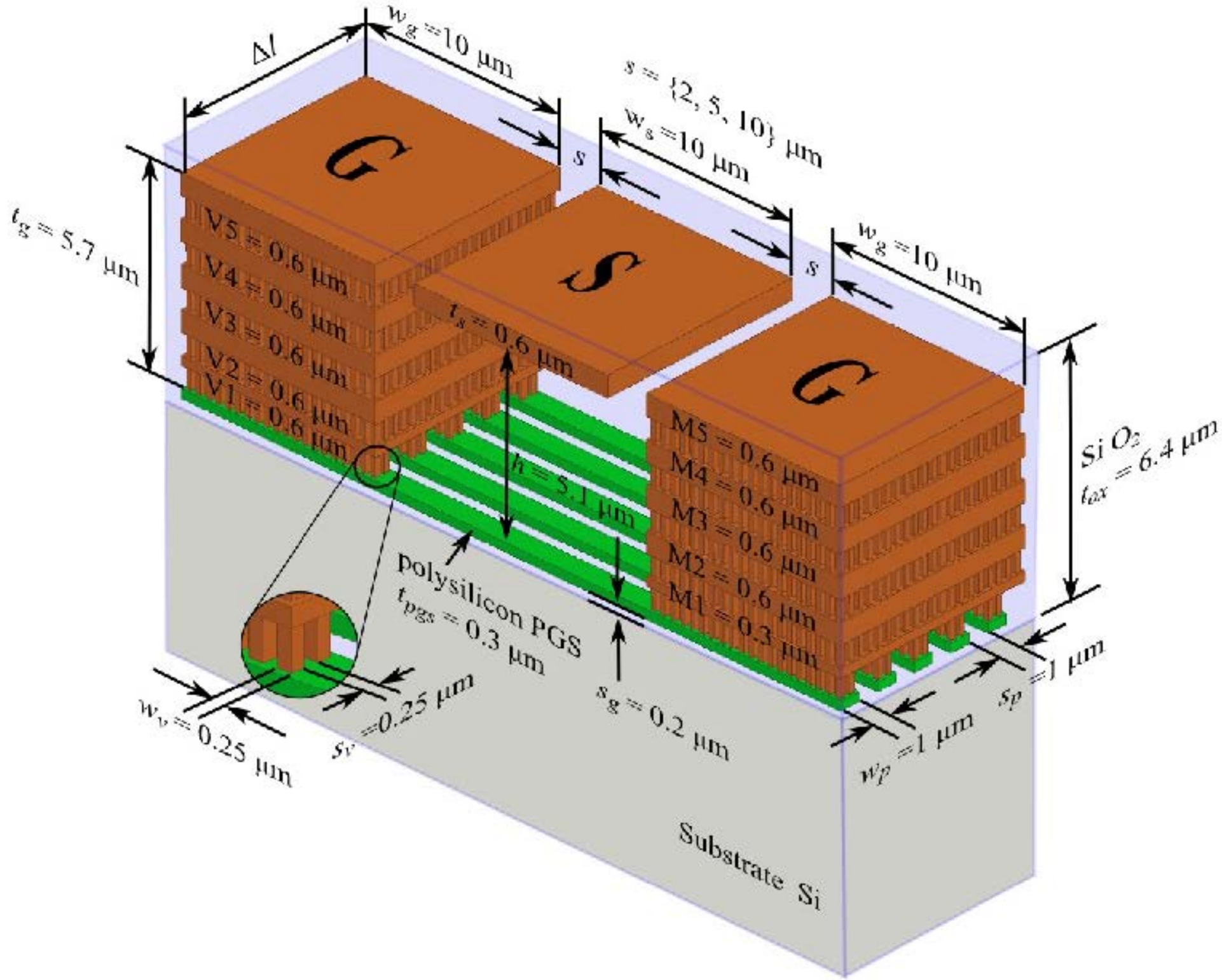
- All ICs require interconnects from device to device, and device to platform (pads).
- These are fundamental parts of the circuit, and thus influence its response to varying degrees.
- In order to have trustworthy simulations, which in turn lead to reliable fabrication, interconnects also have to be characterized and modeled, especially so in the HF regime.
- This work aims at improving the models for Co-Planar Waveguides (CPW), a very common form of interconnect in current technologies.

- The details of the work can be found in:
  J. Valdés, R. Murphy, R. Torres, “Determination of the Contribution of the Ground-Shield Losses to the Microwave Performance of On-Chip Coplanar Waveguides”, IEEE Transactions on Microwave Theory and Techniques, Vol. 69, No. 3, March 2021, pp. 1594-1601. DOI: 10.1109/TMTT.2021.3053548
- Extensive characterization of CPWs has been carried out by many researchers throughout the years.
- Here, we only address two issues, both parasitic: a) Transverse resistance introduced by the PGS. b) Coupling between input and output ports accentuated in relatively short lines.

- The structures available for this study were a "short" line (250 μm) and a "long" line(2,000 μm), in a 50 μm pitch GSG configuration.
- The structures present a different gap-width between the signal and ground lines; 2 μm, 5 μm, and 10 μm.
- They were fabricated at IMEC.
- Measurements were performed using a previously calibrated VNA, using a LRRM routine.


$l_S = 250$ μm
LS3
LS2
LENGTH
LS1
LS4
LS5
LS6
$l_L = 2000$ μm


R_g
L_g
R_s
L_s
R_g
L_g
G_{ox}
C_{ox}
$R_g/2$
$R_g/2$
Δl

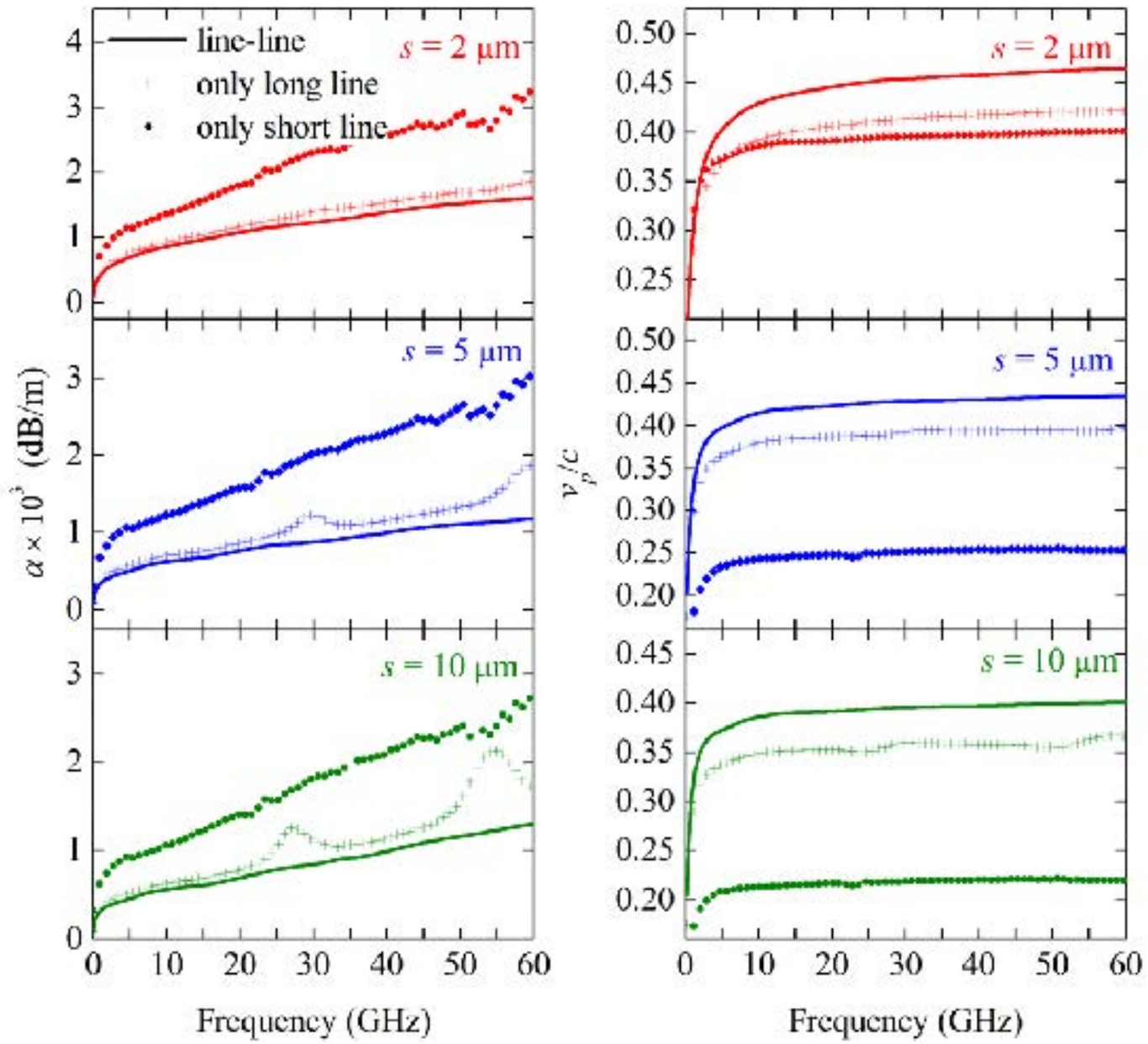

Δl
w_g =10 μm
s = {2, 5, 10} μm
w_s =10 μm
w_g =10 μm
t_g = 5.7 μm
G
S
G
s
s
V5 = 0.6 μm
V4 = 0.6 μm
V3 = 0.6 μm
V2 = 0.6 μm
V1 = 0.6 μm
t_s = 0.6 μm
M5 = 0.6 μm
M4 = 0.6 μm
M3 = 0.6 μm
M2 = 0.6 μm
M1 = 0.3 μm
h = 5.1 μm
Si O_2
t_{ox} = 6.4 μm
Polysilicon PGS
t_{pgs} = 0.3 μm
s_g = 0.2 μm
w_v = 0.25 μm
s_v =0.25 μm
w_p =1 μm
s_p =1 μm
Substrate Si

- Treating CPWs as transmission lines is common practice in RF circuit characterization.
- This way, there is no confusion on whether the measurement should be QS or NQS, as the method applies equally in both cases.
- Thus, the complex propagation “constant” has to be determined from the onset.

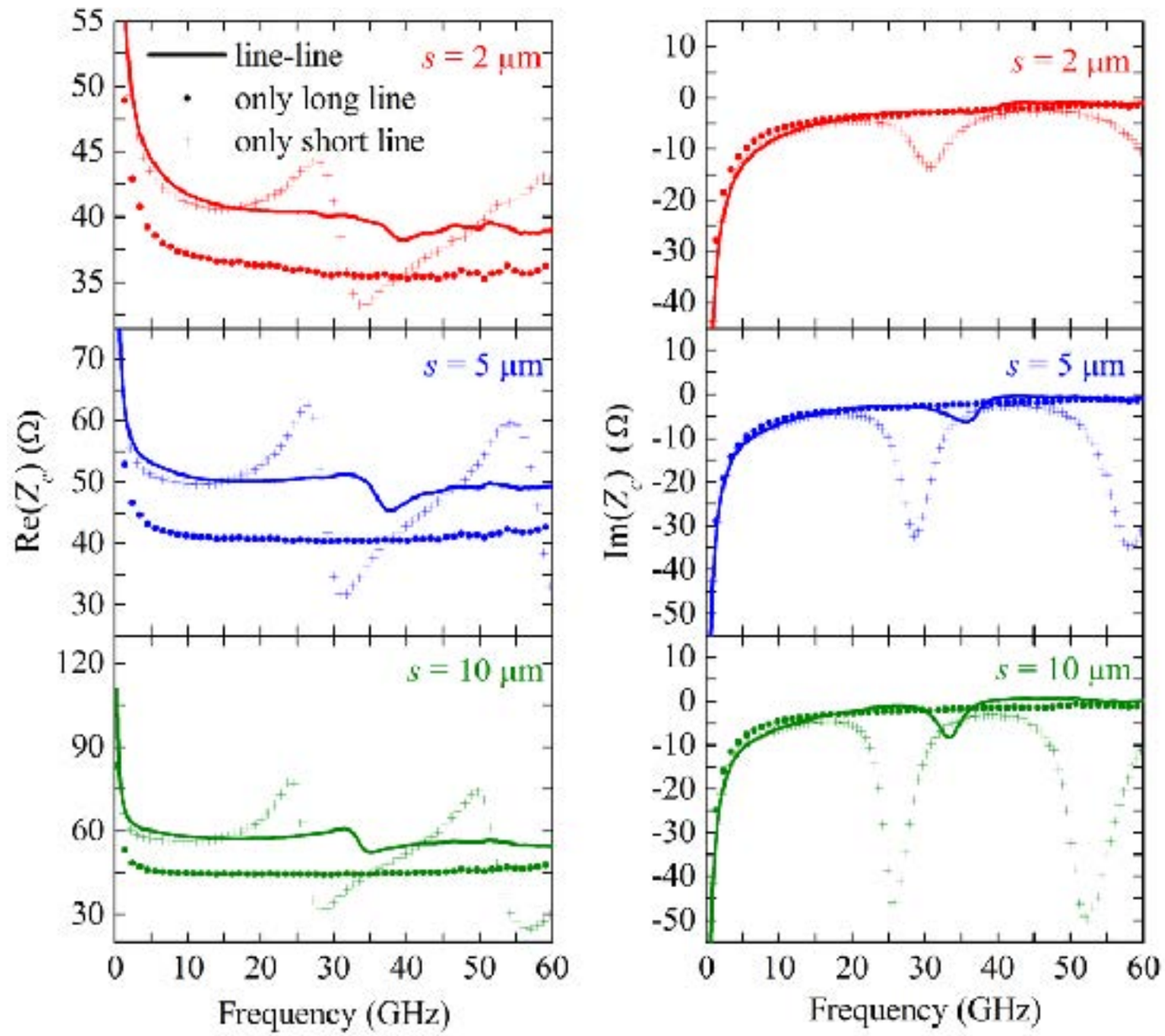
$$\gamma = \alpha + j\beta$$

- Gamma can be deduced from measurements of only one line (line) or of two lines (line-line) with different length but the same cross section.
- The first approach neglects the effects of the pad parasitics, which are more noticeable the shorter the line is.

- **The propagation constant calculated from the long line only is similar in value from the data obtained from the line-line method.**
- **This is not so when using the short line only.**



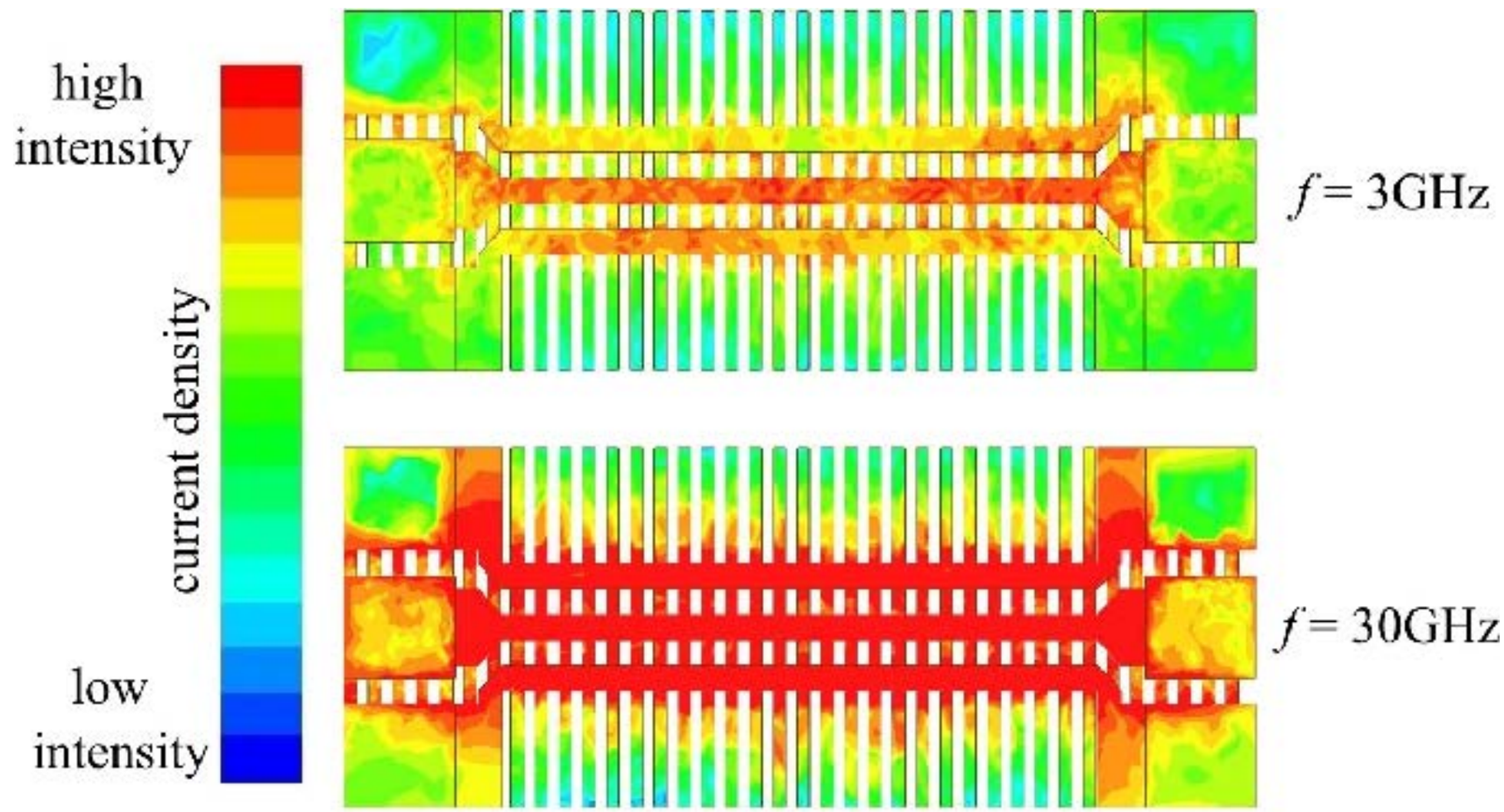
- **Resonances appear when multiples of $\lambda/2$ of the propagating signal equal the length of the line, accentuated by reflections at the pad terminations.**
- **These appear at lower than expected frequencies using the long line.**



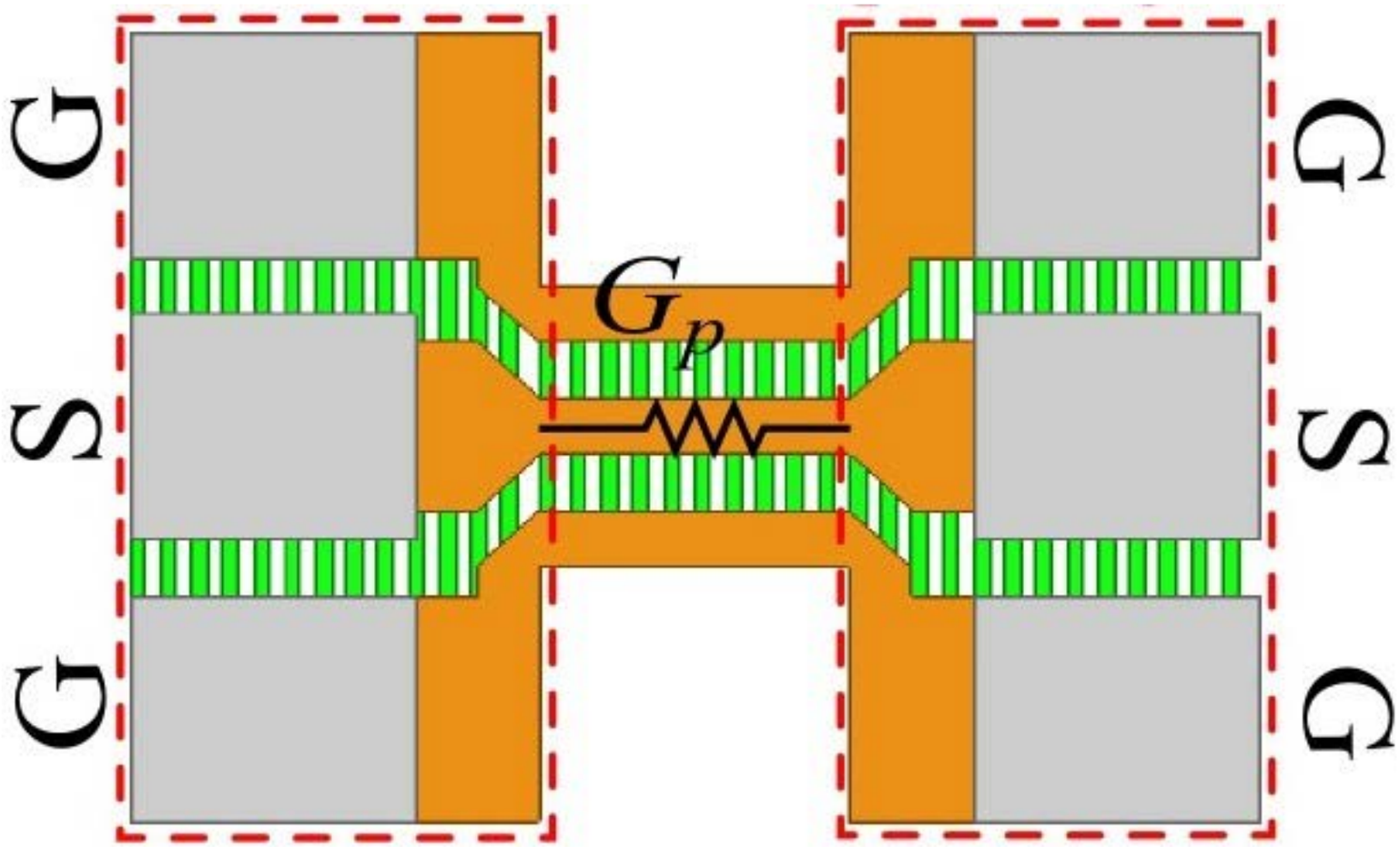
- The problem with the line–line method is the impossibility to completely de-embed the effect of the pad parasitics in the Z_c curves.
- The line–line method shifts the frequency of resonance up to a higher value when comparing with the case in which only the longest line is considered.
- This is attributed to the fact that the effective line length is reduced by the subtraction of the shortest to the longest length.
- The fluctuation of the curves around the frequency of resonance impedes the accurate determination of R, L, C and G per unit length. length.

- Assuming that γ and Z_c obtained using the line–line method are accurate up to a frequency small enough as to avoid the effect of the first resonance in the Z_c curve, the R, L, C and G components can be determined.
- The graphs show that this frequency has to be lower than 20 GHz.
- Once these values are determined, the data can be analyzed up to 60 GHz, and the CPW can be correctly modeled.
- But, we also have to consider another factor which muddles the correct extraction of the values; this is the coupling of the input and output ports, especially in the case of the short line.

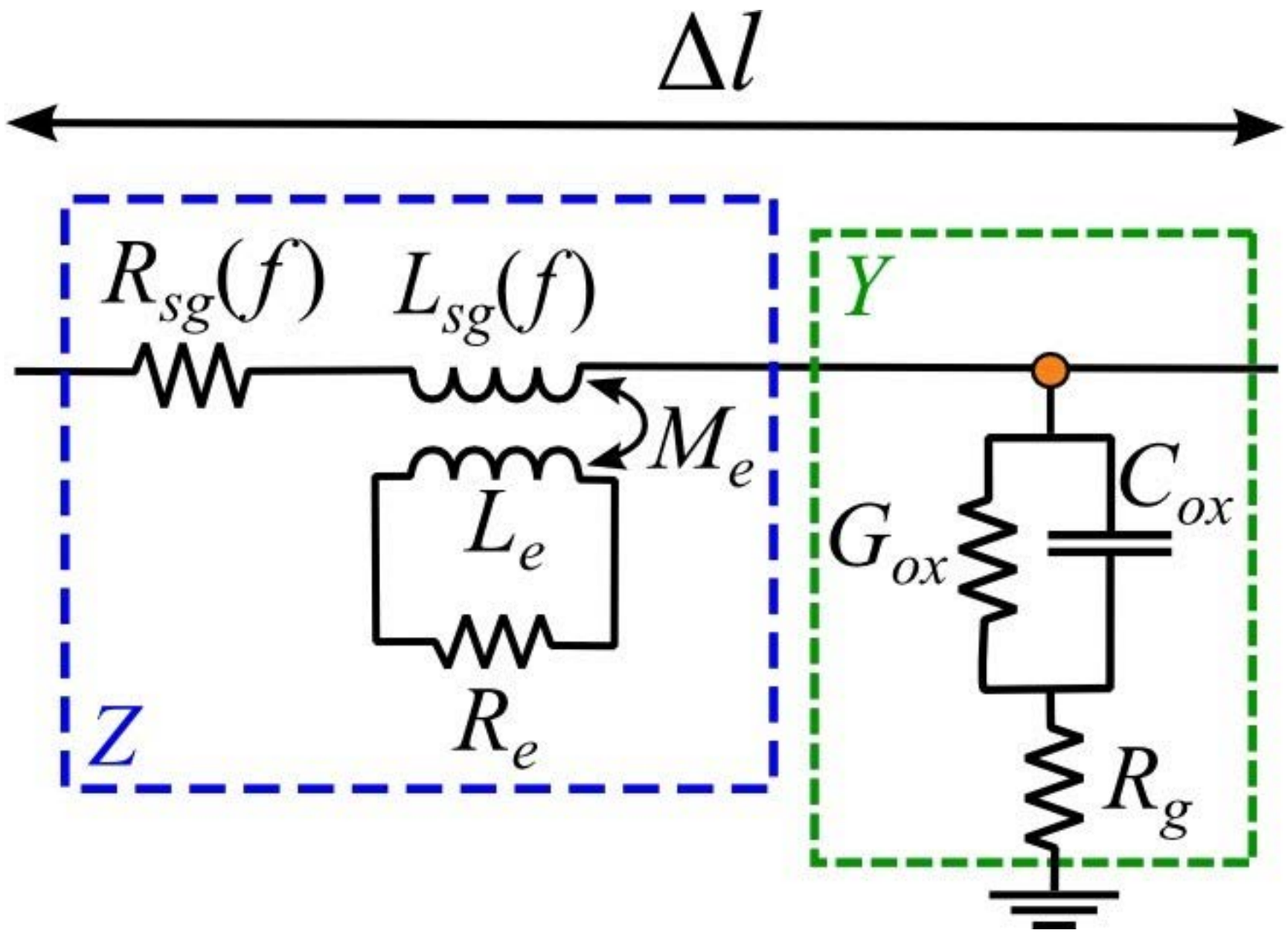
- As in the previous case (integrated inductor) the model considers the dependence of resistance and inductance with frequency.
- An additional component is included to the model to account for the transverse resistance introduced by the PGS, and the coupling between input and output ports.
- This was analyzed for the different gap-width separations.

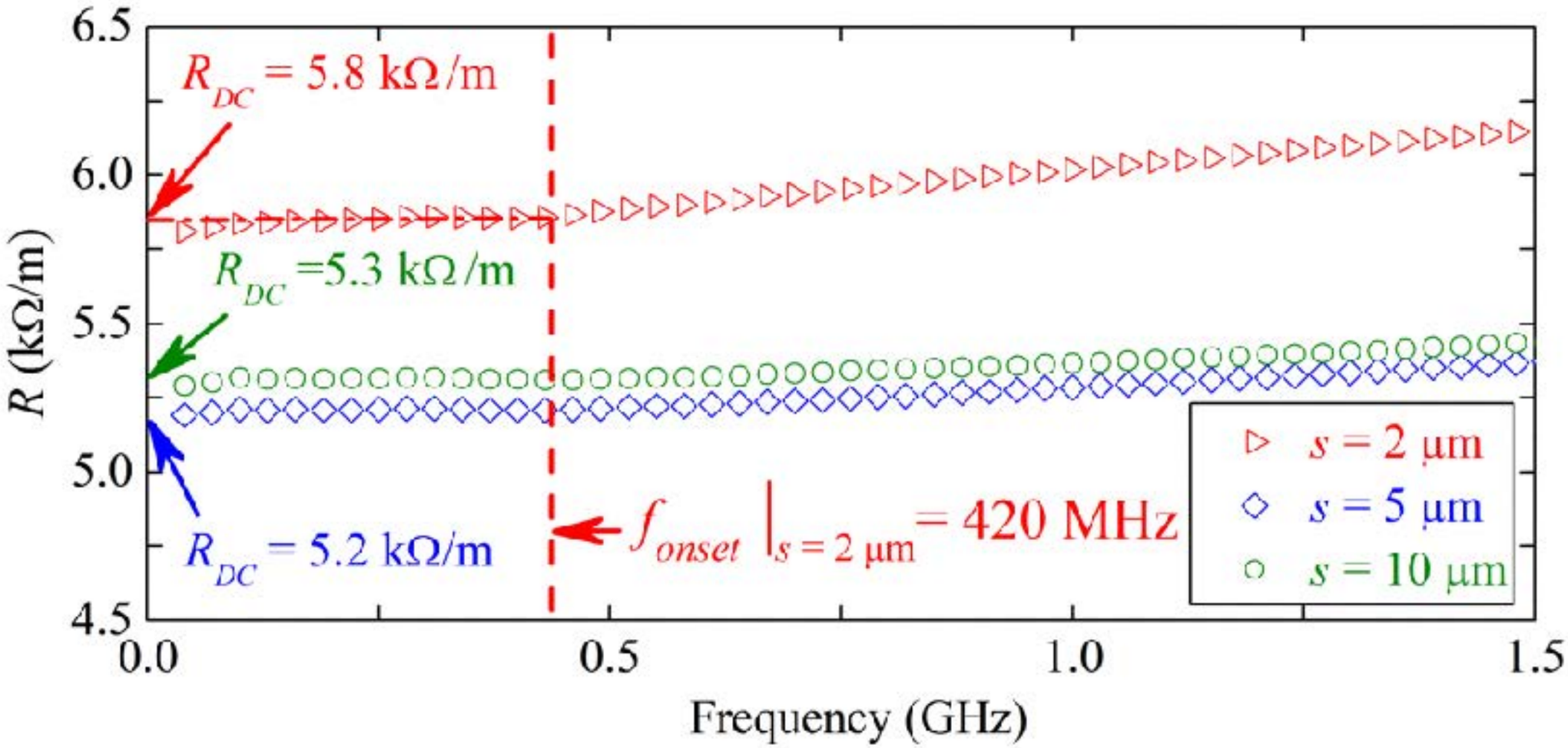


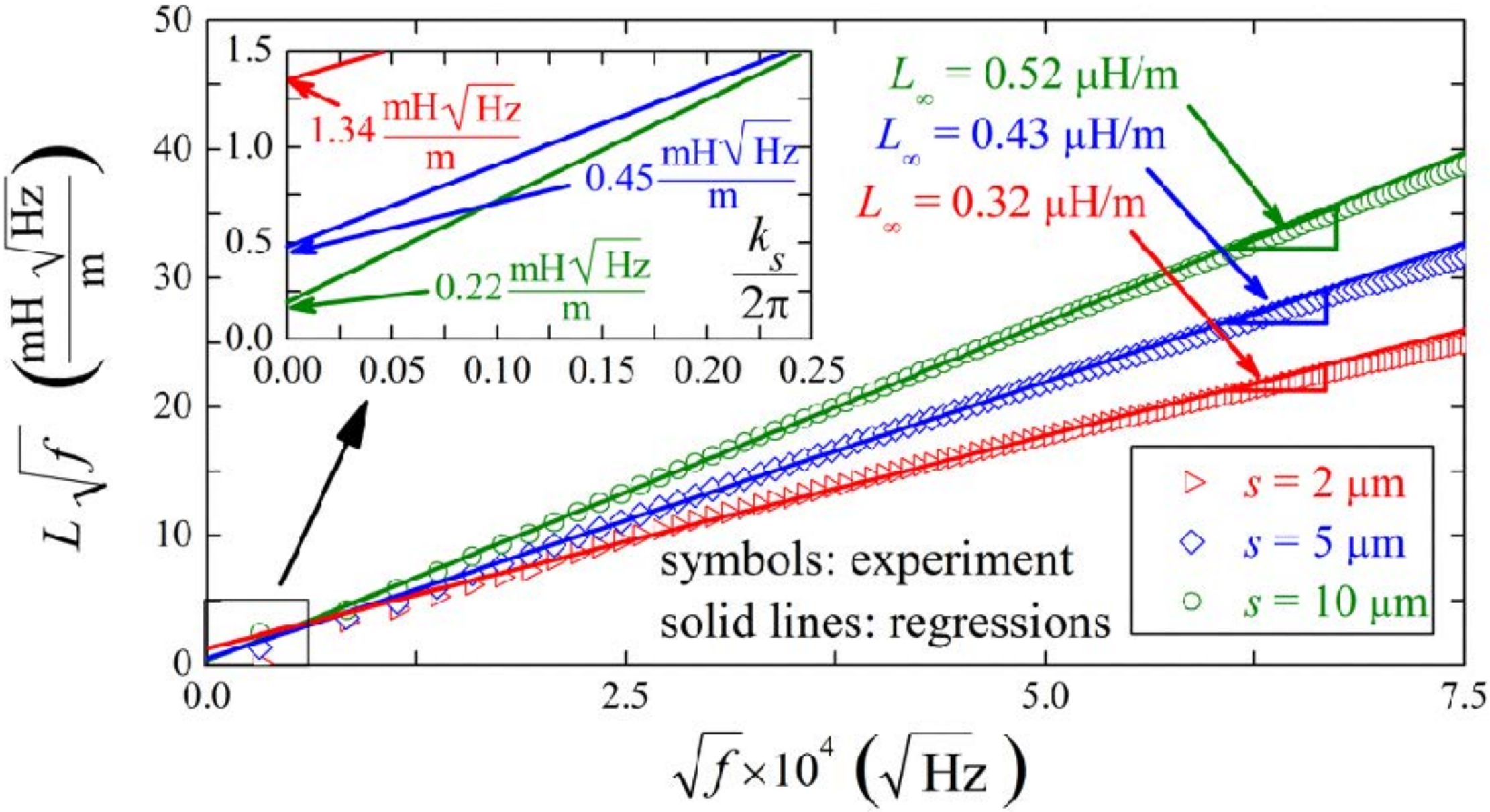
- **Current density substantially increases in the PGS at high frequencies.**
- **The impedance of the shield is reduced with frequency, forming a path in the direction of propagation.**
- **This increases current flow through the shield, and promotes an undesired coupling of the CPW's input and the output ports.**

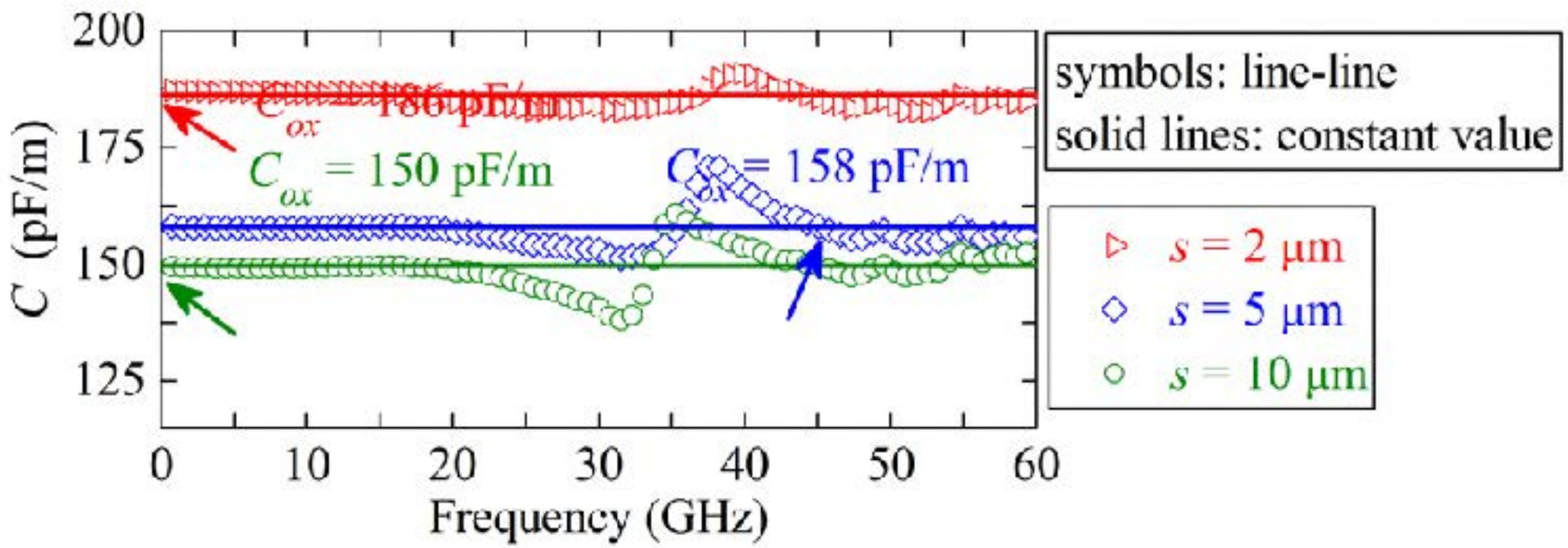


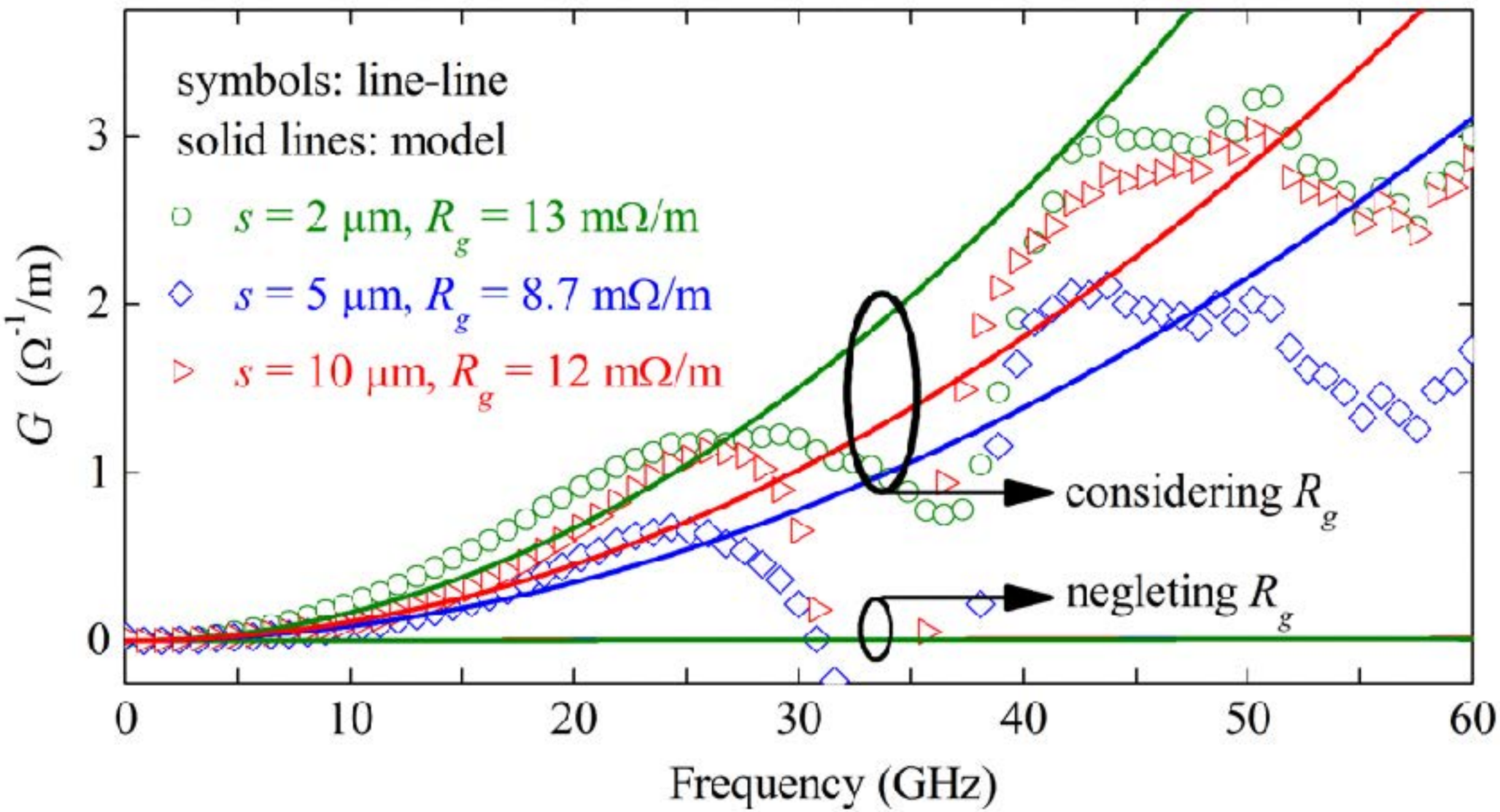
- **This effect is especially noticeable in short lines.**

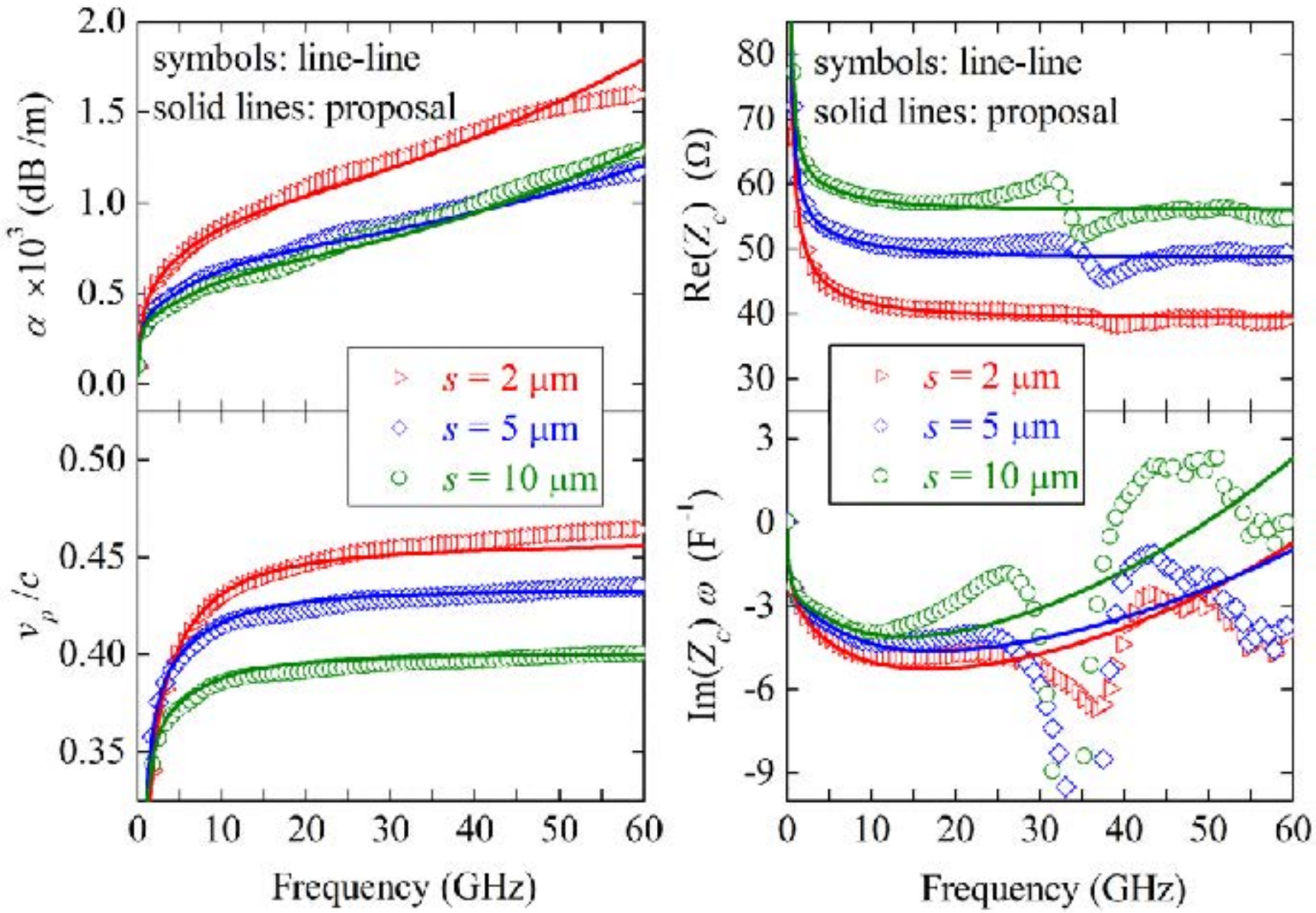

Δl
$R_{sg}(f)$
$L_{sg}(f)$
M_e
L_e
R_e
Z
Y
G_{ox}
C_{ox}
R_g

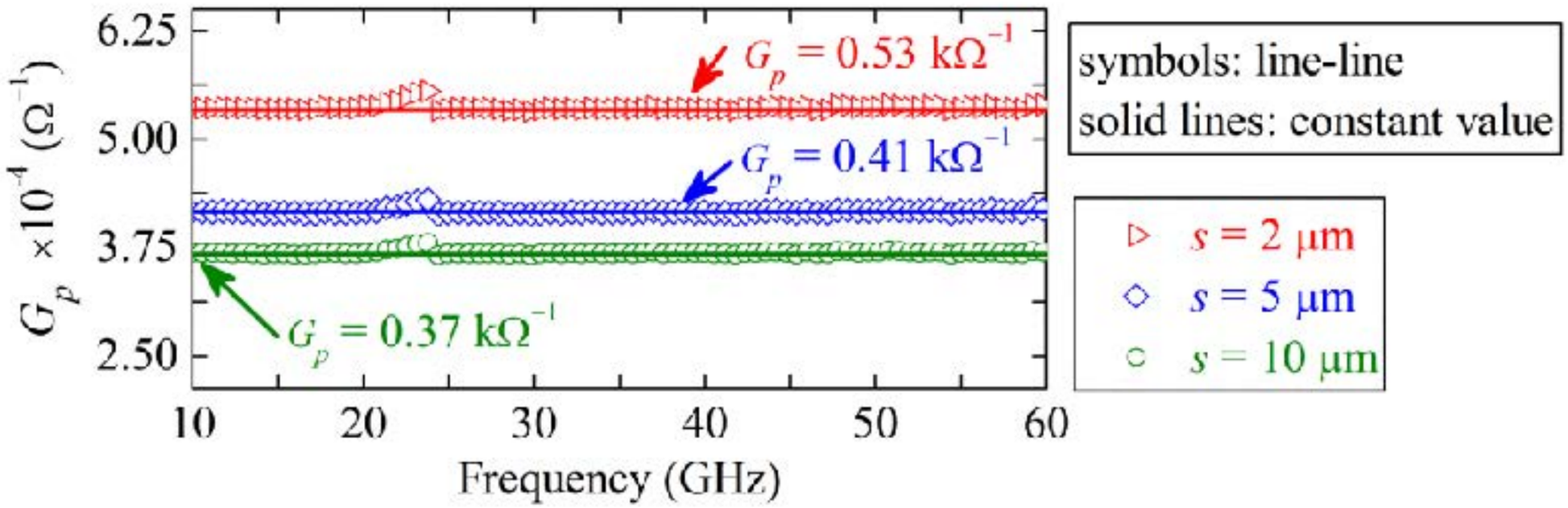

6.5
6.0
5.5
5.0
4.5
R (kΩ/m)
0.0
0.5
1.0
1.5
Frequency (GHz)
R_{DC} = 5.8 kΩ/m
R_{DC} =5.3 kΩ/m
R_{DC} = 5.2 kΩ/m
$f_{onset}\big|_{s=2\,\mu m}$ = 420 MHz
s = 2 μm
s = 5 μm
s = 10 μm

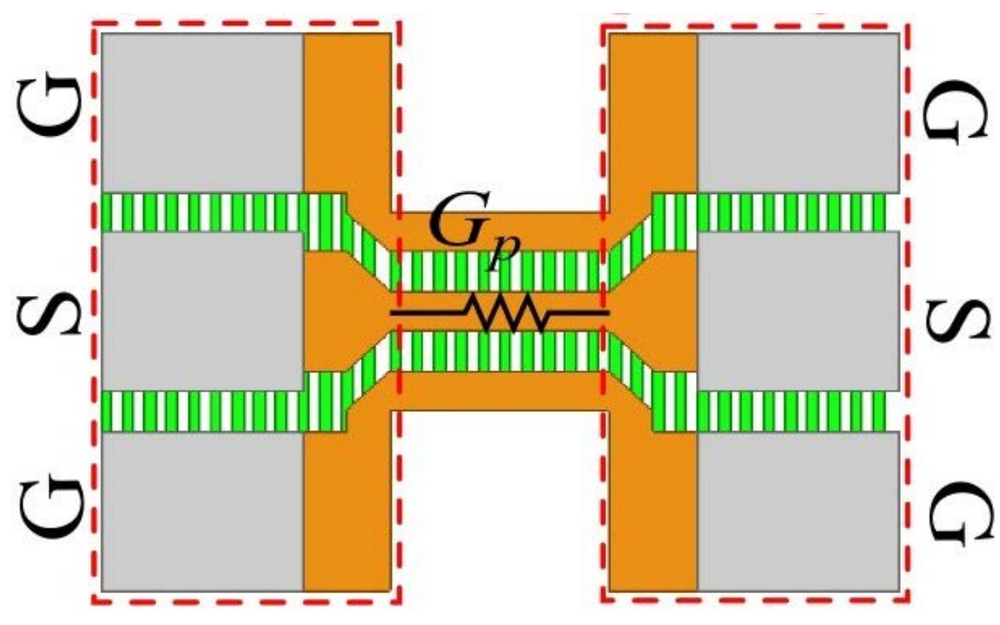

$L_\infty = 0.52$ μH/m
$L_\infty = 0.43$ μH/m
$L_\infty = 0.32$ μH/m
1.34 mH√Hz / m
0.45 mH√Hz / m
0.22 mH√Hz / m
$k_s / 2\pi$
$s = 2$ μm
$s = 5$ μm
$s = 10$ μm
symbols: experiment
solid lines: regressions
$L\sqrt{f}$ (mH √Hz / m)
$\sqrt{f} \times 10^4$ (√Hz)


200
175
150
125
C (pF/m)
0
10
20
30
40
50
60
Frequency (GHz)
C_{ox} = 150 pF/m
C_{ox} = 158 pF/m
symbols: line-line
solid lines: constant value
s = 2 μm
s = 5 μm
s = 10 μm


symbols: line-line
solid lines: model
s = 2 μm, R_g = 13 mΩ/m
s = 5 μm, R_g = 8.7 mΩ/m
s = 10 μm, R_g = 12 mΩ/m
considering R_g
negleting R_g
G (Ω^-1/m)
Frequency (GHz)
0
1
2
3
0
10
20
30
40
50
60


symbols: line-line
solid lines: proposal
$\alpha \times 10^3$ (dB /m)
v_p/c
$s = 2$ μm
$s = 5$ μm
$s = 10$ μm
Frequency (GHz)
symbols: line-line
solid lines: proposal
$\mathrm{Re}(Z_c)$ (Ω)
$\mathrm{Im}(Z_c)\,\omega$ (F^{-1})
$s = 2$ μm
$s = 5$ μm
$s = 10$ μm
Frequency (GHz)


6.25
5.00
3.75
2.50
$G_p \times 10^{-4}$ (Ω^{-1})
10
20
30
40
50
60
Frequency (GHz)
G_p = 0.53 kΩ^{-1}
G_p = 0.41 kΩ^{-1}
G_p = 0.37 kΩ^{-1}
symbols: line-line
solid lines: constant value
s = 2 μm
s = 5 μm
s = 10 μm


G
S
G
G_p
G
S
G

Component	PGS-CPW		
	$s = 2\ \mu m$	$s = 5\ \mu m$	$s = 10\ \mu m$
R_{dc} (kΩ/m)	5.8	5.3	5.2
L_{∞} (μH/m)	0.52	0.43	0.32
k_s (mH $s^{-1/2}$/m)	8.42	2.82	1.38
k	0.137	0.131	0.117
τ (ps)	24.4	21.5	21.4
C_{ox} (pF/m)	186	158	150
R_g (mΩ/m)	9.83	6.6	9.5

Results

- The inclusion of R_g in the proposed model allows the accurate modeling of the behavior of PGS-CPWs at high frequencies.
- The method can be used for other types of lines.
- The challenge of fully de-embedding data using only two lines of different lengths was achieved.
- A systematic and physically based modeling of the undesired coupling of the input and output ports through the shield was developed and demonstrated.

Conclusion

- The field of compact modeling grows in importance day by day, as ever more devices can be fit into an IC.
- Besides active devices, passive ones have to also be modeled in order to guarantee the correct response of the circuit, first at the simulation level, and then in practice.
- Good models also give insight into the physical behavior of the device, circuit or system.
- As technology progresses, the need for more sophisticated ICs arises.
- Thus, compact modeling continues to be a very fertile and promising field of endeavor.

Thank you for your kind attention!