Ultra-High Q-factor Through Fused-silica Via (TFV) Integrated 3D Solenoid Inductor for Millimeter Wave Applications

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Abstract*—In this work, a substrate integrated 3D solenoid inductor is demonstrated using the combination of Through Fused-silica Vias (TFVs) for low substrate loss and Copper (Cu) / Cobalt (Co) metaconductors for low conductor loss, with which a record high three-digit Q-factor is realized in the mmWave range. A solid Cu-based 1 turn 3D solenoid inductor integrated on a 300 μm thick fused-silica with a small form factor of 170 μm x 200 μm shows a peak quality factor of 88.9 at 28.4 GHz. In the meantime, the same design with Cu/Co metaconductor shows a peak quality factor of 204 at 28.4 GHz, showing 130 % Q-factor improvement compared to the Cu counterpart. The magnetic properties of 25 nm thick Co film are characterized using the vibrating sample magnetometer (VSM) technique and are applied to the finite element method (FEM) for analyzing the device performance in the simulation. As the skin effect cancellation effect varies with a function of frequency that is related to the magnetic permeability of Co thin film, the resistance reduction occurs within the range, 21.18 GHz to 48.36 GHz, where the real part of the effective magnetic permeability tensor becomes a negative value. Detail modeling and optimization of the inductors is provided based on the lumped element circuit model and High Frequency Structure Simulator (HFSS) simulation. The impacts on the number of turns, inductor design parameter variation, inductance, and self-resonance frequency (SRF) in the 3D solenoid inductors are provided. Details of prototype fabrication and characterization are also provided.

Keywords— solenoid inductors, Cu/Co metaconductor, low loss conductor, 5G, mmWave, Fused silica, TPV

I. Introduction

The millimeter-wave (mmWave) frequency circuits serve as one of the advanced packaging solutions for modern broadband wireless systems because of their small form factor, high speed, and broad bandwidth while their high RF losses due to the skin effect are yet to be solved. Energy efficient passives are crucial for high signal integrity in an RF front-end (FE) module and integrated voltage regulator (IVR), where an inductor is one of the key components governing overall system performance including power efficiency, phase noise, and thermal noise etc.. The key parameters for inductors are small footprint, high Q-factor, that are related to the dc/ac resistance and dielectric resistance. The inductor dominates the power dissipation from their ac resistance especially at RF frequency band, thus, lowing inductor resistance is necessary in order to achieve high efficiency electronics. However, it is challenging to achieve high-Q inductors especially in mmWave frequency, since the skin depth is inversely proportional to the square root of the frequency and the smaller skin depth in mmWave results in large conductor loss and high ac resistance in inductor, consequently lowering the Q-factor.

To realize a miniaturized and low resistance inductors, on-chip or package integrated inductors that are embedded into the substrate buildup layers have been reported [1-4]. Planar spiral inductors are widely used on the back-end-of-line (BEOL) for their fabrication convenience while they tend to have a low Q-factor because of self-confining eddy current loss in the inner turns. On the other hand, 3D solenoid inductors using Through-Silicon-Via (TSV) and Through-Integrated Fan-Out-Via (TIV) with redistribution layer (RDL) offer a substrate integrated passive architecture and are known to have a higher Q-factor and less coupling with nearby circuits than a 2D spiral counterpart [1-4]. This is because the 3D package integrated inductor offers smaller footprint than 2D inductors and the magnetic field of the 3D solenoid inductor is mainly in the fan-out area [4]. In either case, however, the losses associated with dielectrics and packaging substrate greatly impact the performances of inductors resulting in degrading overall system performance at mmWave frequencies [3]. Alternatively, glass and/or fused-silica substrates have been studied for high efficiency RF systems due to their low dielectric loss (low tan δ), low dielectric constant (low-k), low coefficient of thermal expansion (CTE), between Si and PCB, and high glass transition temperature (high T_g), and their smooth surface roughness compared with the organic counterparts [5-7]. Besides the substrate loss, it is important to notice that the conductor loss associated with the skin effect and proximity effect becomes significant in the mmWave range. Recently, low conductor loss solutions for mmWave application have been reported such as nanoscopic nonferromagnetic/ferromagnetic multilayer structures (as known as metaconductors), with which low loss transmission lines such as coplanar waveguides and coaxial waveguides have been reported [8], [9]. However, a package compatible substrate integrated inductor has not been investigated yet.

In this work, a substrate integrated 3D solenoid inductor is demonstrated using the combination of Through Fused-silica Vias (TFVs) for low substrate loss and Cu/Co metaconductors for low conductor loss, with which a record high three-digit Q-factor is realized in the mmWave range.

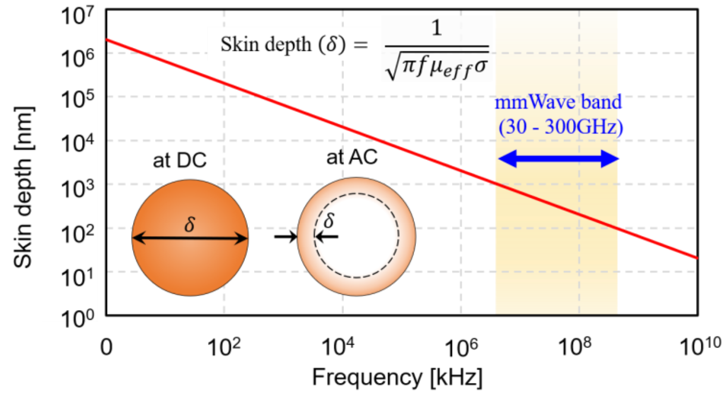


Fig. 1. Skin depth vs. Frequency plot for solid Cu conductor.

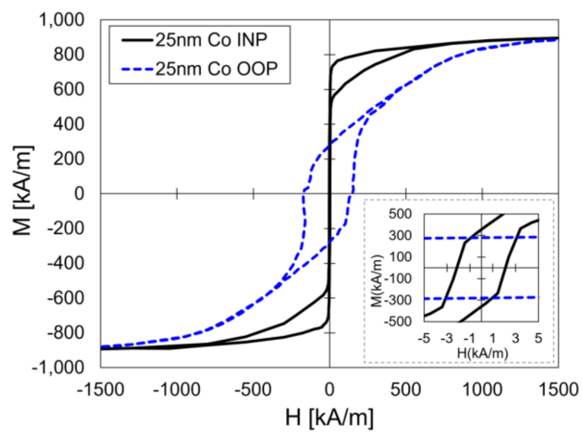


Fig. 2. Demagnetization corrected DC hysteresis of 25nm Co thin film. (Solid line: in-plane and dashed line: out of plane)

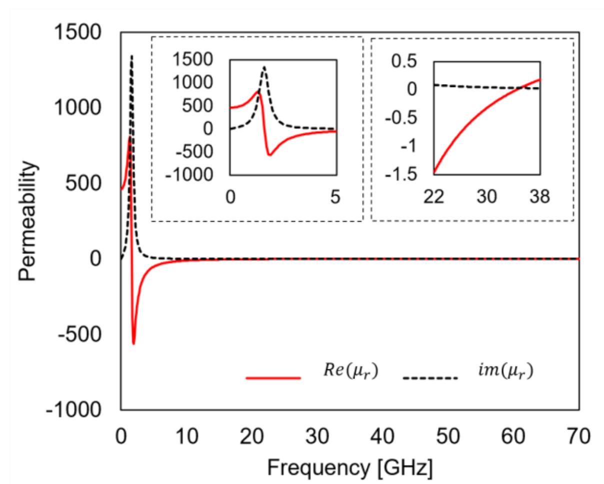


Fig. 3. Calculated permeability tensor of 25nm Co thin film. The real (solid line) and imaginary (dashed line) parts are highlighted.

II. Material Characterization

A. Skin effect

As the skin effect is a function of frequency, this confines the current flow within the outmost conductor area, so called skin depth with which the current density decreases exponentially, especially at mmWave frequency bands, where 5G new radio (NR) bands are included. Fig. 1 shows the skin depth of solid Cu, that is the most widely used conductor, falls below 390 nm above 28 GHz range, thus results in high ac resistance and conductor loss. In the meantime, the ferromagnetic materials such as Cobalt (Co), Nickel (Ni), Iron (Fe), etc. are known to have a frequency dependent negative permeability value ($\mu_r < 0$). By utilizing this negative permeability value along with the other parameters, the effective permeability (μ_{eff}) could possibly become zero, thus, in theory, the skin depth may go to infinity. The relationship between the effective permeability and the skin depth could be explained by the equation:

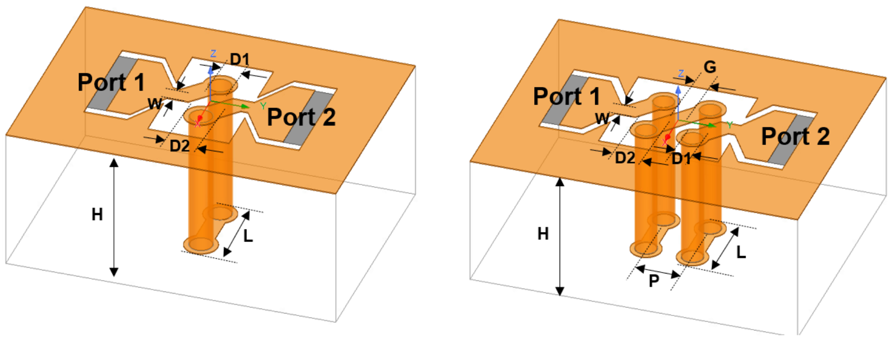
$$\mu_{eff} = \frac{\mu_N t_N + \mu_F t_F}{t_N + t_F} \quad (1)$$

$$skin\ depth \ \rightarrow \infty, \qquad \text{for } \mu_{eff} \rightarrow 0 \quad (2)$$

,where t_N and t_F are the thicknesses, and μ_N and μ_F are the permeability of nonmagnetic and ferromagnetic materials. Previous work showed a maximum 50% resistance reduction at 28GHz range using Cu/Co superlattice structure, so called metaconductor [8], Cu and Co are chosen as a non-magnetic metal and a ferromagnetic metal for 5G NR application. Based on the eq. (1), t_N and t_F are set to be 150nm and 25nm respectively to effectively have the maximum skin depth at 28GHz. In order to verify the concept, the magnetic properties of 25nm Co thin film are measured and calculated in II-*B*.

B. Magnetic material analysis

Based on the previous section, the magnetic properties of 25nm Co thin film are characterized using vibrating sample magnetometer (VSM - ADE Technologies EV9 with a maximum applied field of ±1800 kA/m). The resultant dc magnetic hysteresis curves are shown in Fig. 2. The measured

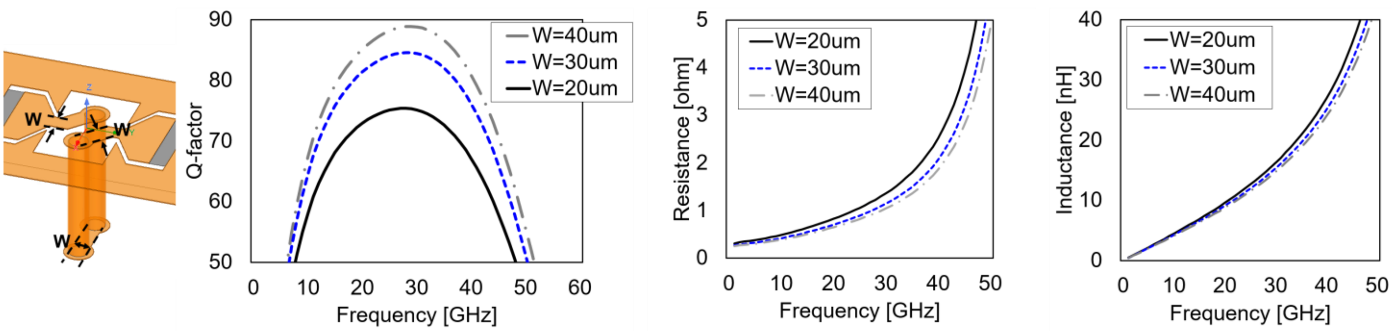


(a) (b)

Fig. 4. The schematic and dimension of the TFV package integrated 3D solenoid inductors. (a) 1 turn and (b) 2 turns

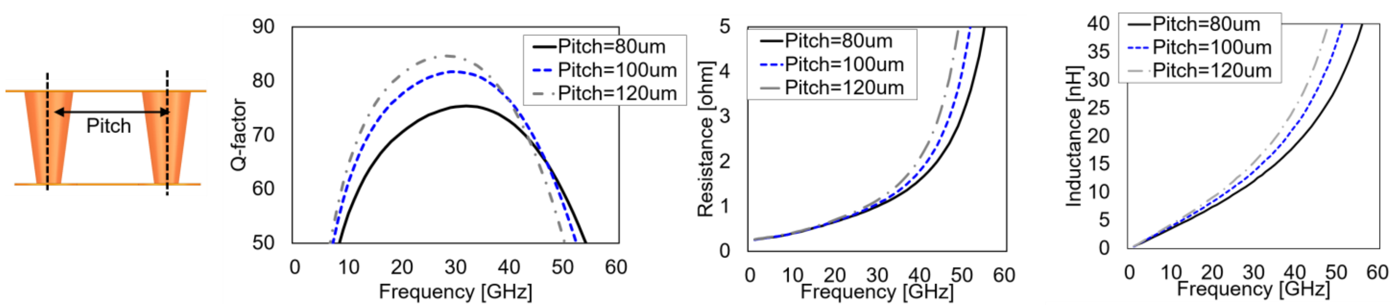
Table I.
Dimension of the designed 3D inductors

Parameter	Specifications
W	20 - 40 μm
G	35 μm
H	300 μm
L	150 - 190 μm
P	105 μm
D1	50 μm
D2	70 μm



(a) (b) (c)

Fig. 5. Design parameter study on the inductor width variation of a solid Cu based 1 turn solenoid inductor (Pitch=120um). (a) Q-factor, (b) Resistance, and (c) Inductance.



(a) (b) (c)

Fig. 6. Design parameter study on the TFV pitch variation of a solid Cu based 1 turn solenoid inductor (W=40um). (a) Q-factor, (b) Resistance, and (c) Inductance.

magnetic properties show the saturation magnetization (Ms) of 1.12 T and the coercivity (Hc) of 24 Oe. Landau-Lifshitz-Gilbert (LLG) equation [8] and Kittel equation [12] are utilized to calculate the magnetic permeability and ferromagnetic resonance (FMR). Based on the FMR and Anti-FMR calculation, the resistance reduction range was estimated between 21.18 GHz and 48.36 GHz. The calculated permeability plot, shown in Fig. 3., is plugged into finite-element method (FEM) and used to simulate the structure.

III. Inductor Modeling and Design

A. Fused-Silica Via integated 3D solenoid inductor

Substrate integrated solenoid inductors possesses structural advantages such as improved inductance density while maintaining high Q factor. High Frequency Structure Simulator (HFSS, ANSYS Inc.) is utilized to design a solid Cu based 3D solenoid inductor integrated with fused silica substrate with dielectric loss (Df) of 0.00002 and dielectric constant (Dk) of 3.79. The designed solenoid inductor models are shown in the fig. 4 with the detailed dimension information provided in Table

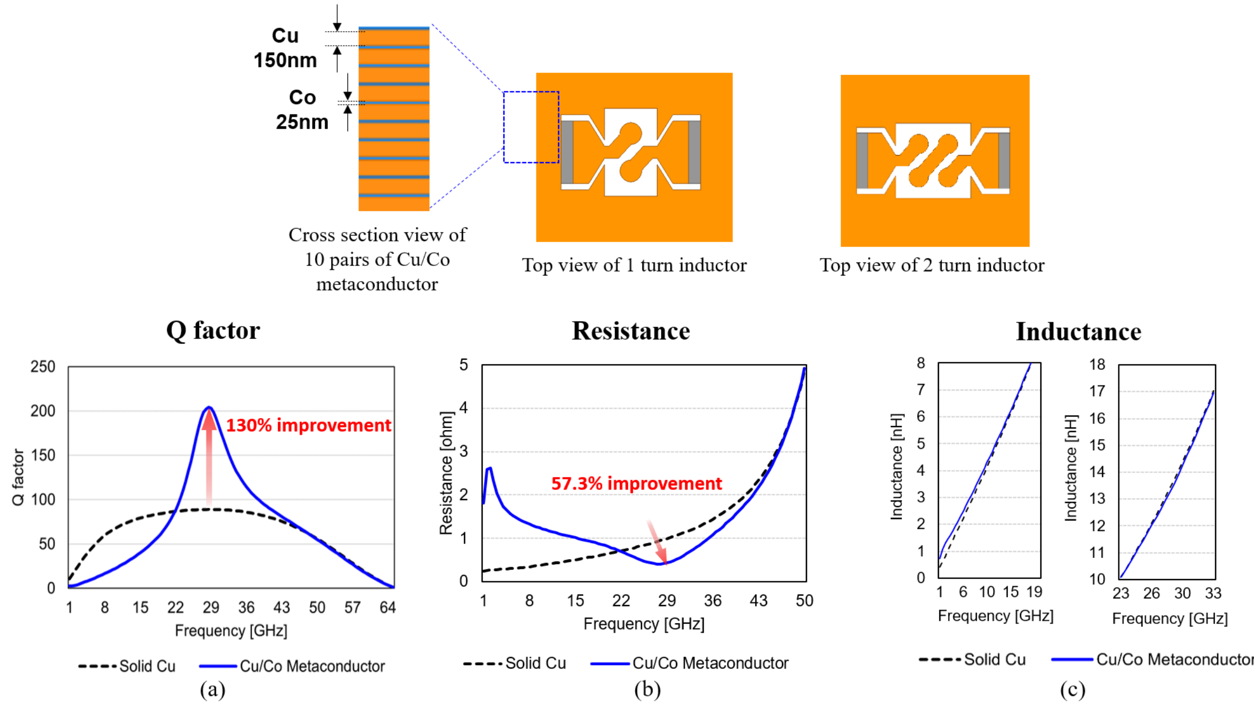


Fig. 7. Simulated performance of the TFV package integrated 1 turn 3D solenoid inductor. Solid Cu (dashed line) and Cu/Co metaconductor (solid line) are highlighted. (a) Q- factor, (b) Resistance, and (c) Inductance

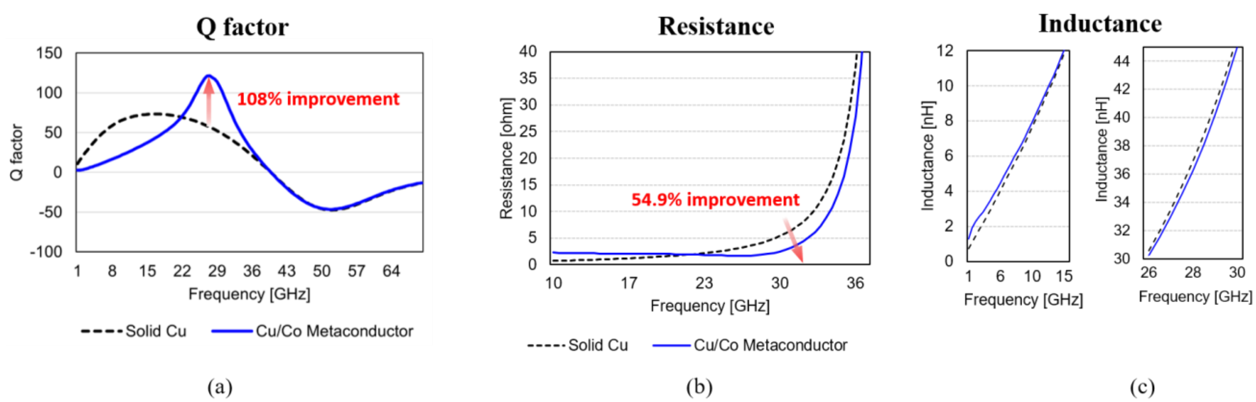


Fig. 8. Simulated performance of the TFV package integrated 2 turn 3D solenoid inductor. Solid Cu (dashed line) and Cu/Co metaconductor (solid line) are highlighted. (a) Q- factor, (b) Resistance, and (c) Inductance

I. The inductor performances with the various design parameters are studied in terms of Q factor, inductance, and resistance. The design parameters such as via pitches and inductor width are varied in FEM, in order to control the inductance density.

B. *Width and pitch effect*

The Q-factor of 3D solenoid inductor is affected by the several design parameters. The inductor width and substrate via pitch impacts on the inductor performances are investigated using FEM. Firstly, inductor width variation is studied, shown in Fig. 5 where the via pitches are fixed as 120 µm. As expected, wider inductor width gives a low resistance and inductance value as the resistance is inversely proportional to the area and the inductance decreases with wider metal width. At 28GHz, inductor width of 20 µm gives the largest inductance of 14.7nH, showing the 8.8% of variation and the resistance of 1.24 ohm with 22.6% of variation compared to the one with 40µm width and this leads to the maximum 17.7% of Q-factor improvement in the 40µm width design compared to the one with 20µm width. In Fig. 6, the impact on TFV pitch variation is studied as well where the inductor width is fixed as 40µm. The smallest pitch of 80µm shows the smallest resistance of 0.92 ohm with 12% variation and inductance of 11nH with 26.4% of maximum difference. Highest Q factor is observed in 120µm pitch model showing 13.1% of improvement compared to 80µm pitch model.

C. *Cu/Co metaconductor based inductor*

The performances of solid Cu based 1, 2 turn solenoid inductors are compared with the one with Cu/Co metaconductor. For the effective skin effect cancellation, the

Table II.
Summary of the simulated 3D inductors performances (Cu vs. Cu/Co)

# of turns	Size	Conductor type	Resistance	Inductance	Self-Resonant frequency (SRF)	Q factor
1	170 μm x 200 μm x 300 μm	Cu	0.96 Ω	13.38 nH	65.37 GHz	88.90 @ 28GHz
		Cu/Co	0.41 Ω	13.23 nH	65.37 GHz	204.13 @ 28GHz
2	200 μm x 200 μm x 300 μm	Cu	4.5 Ω	36.92 nH	39.75 GHz	73.07 @ 17.54 GHz
						58.16 @ 28 GHz
		Cu/Co	2.03 Ω	36.23 nH	39.75 GHz	121.48 @ 28 GHz

metaconductor with 10 pairs of Cu/Co (150 nm/25 nm) thin layers is used for comparison, the cross section view of metaconductor is shown in Fig. 7. The designed inductor width and TFV pitch are fixed as 40μm and 120μm respectively. The simulation results are summarized in Table II. At 28 GHz range, 1 turn and 2 turn solenoid inductor show the maximum resistance reduction of 57.3%, 54.9% and 130%, 108% of the Q factor improvement, respectively, compared with the solid Cu based inductor counterpart. Three digit Q factor, that hasn't been reported yet, is achieved by replacing the conventional Cu with Cu/Co metaconductor. The advantage of Cu/Co metaconductor is that it can be utilized in any structures containing conductors, resulting in the ultra low resistance characteristic and the substantial improvement in the device performance. In conclusion, the Cu/Co metaconductor inductors has a superior performance over a solid Cu based inductors.

IV. Fabrication and Characetrization

A. *Fabrication and characterization*

The prototypes will be fabricated using the Cu/Co metaconductor and the solid Cu reference conductor. A 300μm thick 4" ultra low loss fused silica wafer will be used as a substrate. After via formation, substrate will be cleaned by piranha cleaning. Top layer inductors are patterned, followed by metalization. The same process will be repeated on the bottom layer. The devices will be characterized using a PNA Network Analyzer and the inductor parameters will be calculated based on the measured electrical response.

B. *Tapered via effect*

The through package via (TPV) process in glass or fused silica substrate is different from the TSVs formation that has an anisotropic sidewall. They are formed by various methods with the taper angles, ranging from 75° to 90° depending on the processes used [11]. Thus, the via formation process tolerance will possibly affect the device performance. As the 3D solenoid inductors include the TPVs as part of the design, the investigation on the tapered via effects seems to be necessary. The tapered via effects are studied in HFSS by varying the angle (θ) in the simulation. It is assumed that all the vias are filled with a conformal metal coating. Fig. 9 shows the simulation results of its impact on the Q factor of a 1 turn solenoid inductor. The maximum Q factor is observed with a straight via model (θ=90°). The tapered via effect causes additional losses and

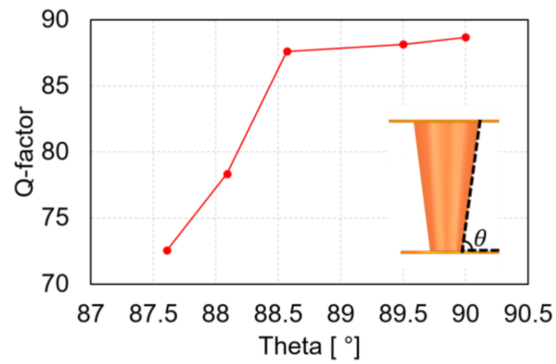


Fig. 9. Simulated tapered via angle effect on the Q factor of a 1 turn 3D solenoid inductor.

showed the maximum 22.2% of Q faction variation. Thus, Q factor variation will be observed depending on the different TPV processes, leading to inductor performance degradation compared to the simulation results.

V. Conclusion

In this work, a TFV integrated 3D solenoid inductor is demonstrated using Cu/Co metaconductors for low conductor loss. The simulation results show a record high three-digit Q-factor in the mmWave range. A solid Cu-based 1 turn 3D solenoid inductor integrated on a 300 μm thick fused-silica shows a peak quality factor of 88.9 at 28.4 GHz and the same design with Cu/Co metaconductor shows a peak quality factor of 204 at 28.4 GHz, showing 130 % Q-factor improvement compared to the Cu counterpart. The design parameter impacts, such as inductor width, TPV pitch, and TPV tapered angle variation, on the inductor performance are explored using FEM in HFSS.

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