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Technical Development of Smart Phone Wireless Charging Receiving Coil Module

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Abstract. Most of mobile phone wireless charging design are in similar architecture as WPC Qi standard defines duo to interoperation requirement between chargers and phones from different brands, and the introduction of magnetic attachment helps improve charging efficiency by better alignment between two coils from charger and phone. Multipole magnets can improve attraction force which can help create thinner magnet when space limited or cost down by reducing quantity of magnets while still keep adequate attachment force. For measuring magnetic characteristics of nanocrystal for design simulation, the classical method which is to measure material itself is not accurate enough, it's proposed to conduct measuring with physically similar condition as real application. The major requirement of coil design is to reduce efficiency loss and heat generation by reducing conductive loss and inductive loss, wire wounded receiving coil is with big section area, especially when using square section wire, and FPC coil can be designed with difference trace width plus twisting between each of the two layers, e,g. outer trace is width and inner trace narrow down with twists, or with trace width narrow done gradually from outer to inner. For high power charging models, 2 coils can be connected in-parallel or in-serial when charging in higher or lower power respectively.

Keywords: wireless charging; receiving coil; nanocrystal; multipole magnets.

1. Introduction

Due to interoperation between different charger and mobile phone brands, most of phone makers design their wireless charging coil module in similar architecture as WPC (Wireless Power Consortium) Qi standard defines. Although there still famous brands phone without introducing magnetic attachment yet, with charging power increasing, 2 coils' alignment between charger and phone are increasingly important for charging efficiency which can be improved by magnetic attachment, on the other hand, magnetic supply chain is more mature driven by Apple's Magsafe. Magnetic attachment was defined in MPP (Magnetic Power Profile) of Qi standard with, this facilitate WPC members' adoption without IP risk, and now most top phone brands are actively involving new high power Qi standard's development, which is expected to be release soon, so high power charging with magnetic attachment is promising to become main stream technical configuration[1] [2].

Receiving (Rx) coil module of mobile phone wireless charging is mainly consist of Rx coil, magnet array for magnetic attachment, nanocrystal sheet and copper shielding. The Rx coil is core part to induce electrical energy from magnetic field excited by transmitting (Tx) coil like a in planar transformer. The magnet array is of 10+ arc magnets distributed circumferentially around the outside of coil, works together with their counter magnets inside charging to ensure 2 coils alignment in charger and phone respectively, so as to improve charging efficiency and reduce heat generation. The nanocrystal sheet with higher permeability sticks onto Rx coil from battery side, which adapt most of magnetic flux recieved back to Tx direction without penetrating into battery cover and causing eddy current. Copper shielding stick onto nanocrystal sheet on a surface opposite the coil, act as final magnetic decoupling from wireless charging module to battery [3].

This paper reviews the latest technology progress and new potential of Rx coil module for mobile phone wireless charging. Next sections cover the below content in sequence: 1) magnet array for

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magnetic attachment, more attention is focued on new practice of multi-pole magnet to improve attraction force. 2) nanocrystal sheet, emphasized point is about how to get accurate value of magnetic characteristics for coil module design simulation, on which the traditional material measurement method is not adequate. 3) Rx coil, since ACR and DCR of Rx coil have been identified as top two major sources of charging loss, this section focus on solutions to reduce conductive and inductive loss, including hybrid FPC Litz wire, identical turns FPC coil and a in-parrallel and in-serial connection switchable coil aiming for high power and low power working condition respectively. Finally, a conclusion section added with also proposals to study on new emerging features.

2. Technical development of wireless charging Rx coil module

2.1. Magnet

The manufacture technology of magnet has been improved significantly driven by Magsafe and new emerging applications like mini motors, the model selected for Rx magnetic attachment has upgrade from N45SH of Iphone12 in 2020 to N52 level for mid- and hi-end phones today, while there are also other brands phone reducing quantity of magnets from the array for cost down while still keep higher attraction force than Qi standard defines. In addition, the most commonly used Nd-Fe-B magnet contains heavy rare earth Dy and Tb, for purpose of either increasing magnet supply or coping with trading regulation, several companies from China and EU claim they have heavy-rare-earth free solution, but by now there still no testified maturing offering for higher grade alternation which can sustain 100°C experiment, e.g. for automotive grade.Since from the adoption of Magsafe which is Iphone's magnetic attachment solution till 2025, all magnets for attachment are with two magnetic poles, e,g. MPP of Qi standard defines S-N from outer to inner along radial direction as in Fig.1.(a) and (c). The N-S-S-N multi-pole magnet which have been adopted by motor and bear industries can increase strength of magnetic field so does attraction force, in mobile phone, it can be used either for thinner magnet when space limited, or simply for cost down which is to improve attraction force in single magnet level and reduce magnet quantify in its array. Iphone Air released in Fall of 2025 reduces magnet thickness to around 0.3mm (while add width) by NSSN magnet as in Fig.1(b) and (d).

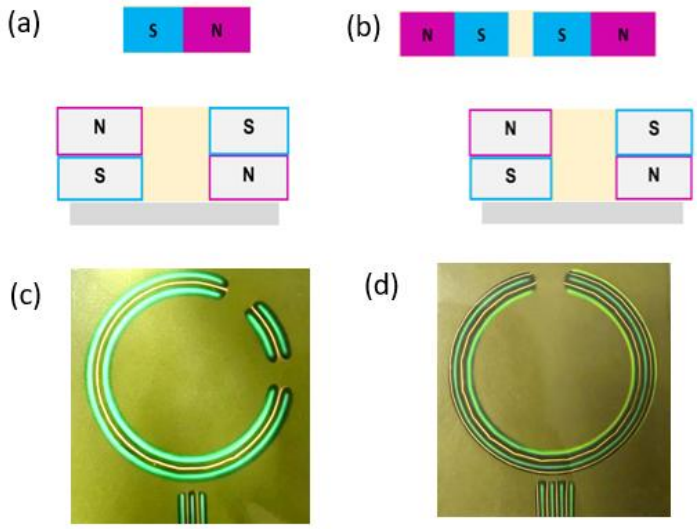
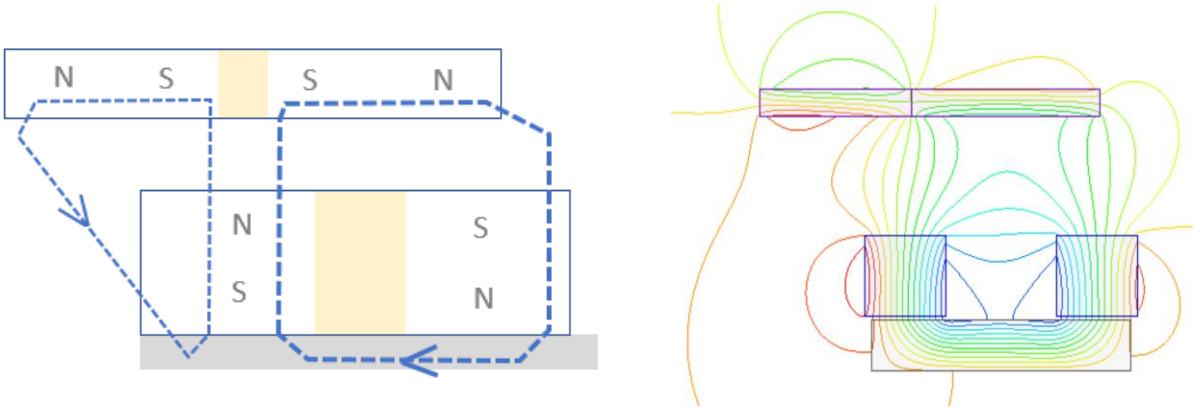


Fig. 1 Magnet poles distribution: (a) normal design; (b) NSSN; Magnet flux image: (c) Iphone 17E – normal design; (d) Iphone Air-NSSN. (Picture credit : Original)

The unibody NSSN magnet in Rx module adds a N-S pair outside the original S-N pair in radial direction, which forms two magnetic flux loops with standard magnet inside charger as in Fig.2(a). The repelling between two adjacent S-poles press flux convergingly and create strong attraction force with the closest N-pole from charger, additional attraction force also come from the magnet volume increasing by extra width added. Therefore, this NSSN solution for Rx is able to provide clearly increased attaching force including both attraction in normal direction and shear force [4]. It's found

from simulation that, the major value of this NSSN is to gathering magnetic flux between two adjacent S-pole and direct it towards N-pole of charger, the involvement of out most N-pole is not remarkable as in Fig.2(b), therefore, when magnetizing, there is no need for 4 poles to be in same size and arranged uniformly.



(a) (b)

Fig. 2 NSSN Rx mates with normal Tx, (a) 2 flux paths; (b) magnetic field distribution. (Picture credit : Original)

In recent years, several patents of mainstream mobile phone brands claim innovation points related a toroidal Halbach magnet array, in which the direction of N-S pair continually rotate 90° from its neighbor, its famous advantage is to concentrate magnetic field to one side and significantly reduce it on another side. But the 90° alternation cause half number of magnets in the array with N-S poles distributing along 0.3-0.4mm magnet thickness direction, it's too thin to prevent them from de-magnetizing. While the NSSN with 180° N-S pole alternation is good for both manufacturability and magnetization stability. The successful adoption of NSSN may catalyze more innovation efforts towards irregular magnetic pole distribution from conventional bi-pole practice.

2.2. Nano-crystal sheet

Nano-crystal used for mobile phone wireless charging is made of Fe-based amorphous ribbon by heat treatment with nucleating agent and grain boundary agents. The produced crystalline ribbon is stick with adhesive then go for fragmentation process ending up with flakes on roughly stable and unified size acc. to pre-defined permeability. 5-11 layers such nano-crystalline foil are stacked toogether and form a nano-crystalline sheet for Rx coil module usage. Only few companies in the world have core competence for this kind of amorphous ribbon and nano-crystal innovation, very rare open report available about essential nano-crystalline innovation for mobile phone wireless charging. General speak, the expected technical direction is for low loss tangent, and higher saturation resistance.

The magnetic characteristics of Nano-crystal are critical for wireless charging, but the classical method of measuring permeability and loss tangent is not adequate to give accurate value for design simulation.

Current practice to measure magnetic material is to use magnetic ring in a pre-defined size. Specifically, for nanocrystal sheet, the measured sample is made by, 1) cutting the sheet together with its adhesive and release liner into standard ring shape, the shape and size is defined by measurement instrument maker; 2) stack several layers of the above cut sheet into a nanocrystal core. When input thickness of nanocrystal core for result calculation, the thickness of adhesive, and also of release liner if present, should be deduced. The most commonly used measurement instrument is Keysight Impedance Analyzer E4990A used with Keysight 16454A magnetic material test fixture. The fixture parts of 16454A can be assembled into a sealed hollow copper cylinder with a copper shaft in the middle; when nanocrystal core be placed inside the cavity, the outer shell and inside shaft can form a single turn coil around nanocrystal core as in Fig. 3; measure inductance and resistance of the coil with and without nanocrystal core, permeability and loss can calculated from the measured result [5].

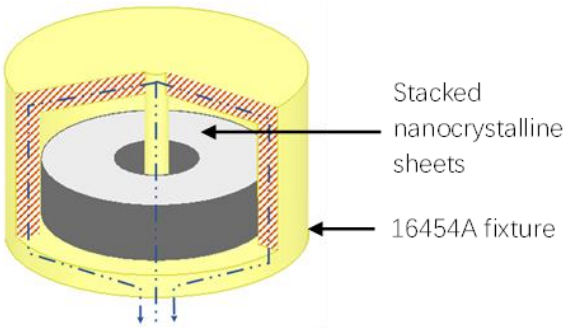


Fig. 3 Illustration of magnetic material tested in Keysight 16454A. (Picture credit : Original)

The accuracy of measurement result when tanσ<0.1 can be calculated as below formula from instrument maker, the measurement error of μ_r' is "4% ++", and it's still unknow what about situation of tanσ>0.1 [6].

μ'_r Accuracy $@\tan\delta < 0.1$

$$4 + \frac{25}{F\mu'_{rm}} + \left(\frac{0.1}{F\mu'_{rm}f}\right) \tag{1}$$

Loss Tangent Accuracy of $\mu_r(\Delta\tan\delta)$ $@\tan\delta < 0.1$

$$0.002 + \frac{0.001}{F\mu'_{rm}f} + \frac{\Delta\mu'_{rm}}{\mu'_{rm}}\frac{\tan\delta}{100} \tag{2}$$

Where μ'_r is complex permeability; f is measurement frequency; $F\mu'_{rm}$ is related to dimensions of fixture and measured sample [mm]; tan δ is the measured value of loss tangent; μ'_{rm} is the measured value of permeability; Δis spread of measured value.

Another source of inaccuracy may come from difference between measurement condition and real working condition. When wireless charging, it's a planar coil sticking with a nanocrystal sheet, and in many cases, surrounding by MPP permanent magnet array, the magnet will add bias magnet field onto edge area of nanocrystal sheet.

One improvement is using 2 nanocrystal sheets sticking on both surfaces of a PCB with spiral coil printed. By simulation a 3D permeability-frequency-inductance mapping surface is created, with measured inductance under certain frequency, permeability can be determined from the 3D surface [7]. The advantage of this method is that, the coil and nanocrystal can be in a status similar as real application, for both geometry and magnetic interaction, instead of a 3D core inside cylinder cavity. Also the coil PCB is sealed by 2 nanocrystal sheets from both sides, with very less flux leakage so the measurement is with good sensitivity. But this solution does not take in account of affection from Tx side, so the magnetic field is still not aligned with real situation, while Ls and Rs are subject to change under different magnetic fields.

As suggestion for further studies, a test set-up closing to real application could be helpful when deriving permeability from measured Ls and Rs.

2.3. Receiving Coil

Receiving coil acc. to Qi standard is a circular planar coil, there are two main stream categories by different manufacture process, 1) wire-winding, which consist of multiple strands, e.g. 7 strands, of insulated copper wire connected at the end, and winds side-by-side in a flat spiral from inside out. This splitting configure is to provide enough section area per turn with limited thickness, while minimize loss by eddy current. Iphones keep using wire winding Rx coil as in Fig.4(a). 2) FPC coil, etched copper coil traces are located on 2 side of FPC -Flexible Print Circuit. This is the form Samsung and Huawei adopt for years as in Fig.4(b).



(a) (b)

Fig. 4 Rx coil in mobile phone: (a)Iphone 17E by wire winding; (b)XiaoMi 10 by FPC with print mark removed by AI. (Picture credit : Original)

Wire charging user are more sensitive on charging speed and temperature rising, both are directly related to charging power and loss. In product development phase, with fixed specification of charging power, reducing Loss from different origins and improve charging efficiency is important.

Wireless charging system of mobile phone can be simplified as CLLC model as in Fig. 5 [7]. C is capacitor, L is inductor. A inverter applies AC voltage onto transmitting (Tx) coil inside charger, the receiving (Rx) coil inside mobile phone induces electrical energy from alternative magnetic field excited by the Tx coil, bridge in rectifier convert AC to DC and charge to battery. Inside dot line are the coupling section including coil modules from both charger and phone.

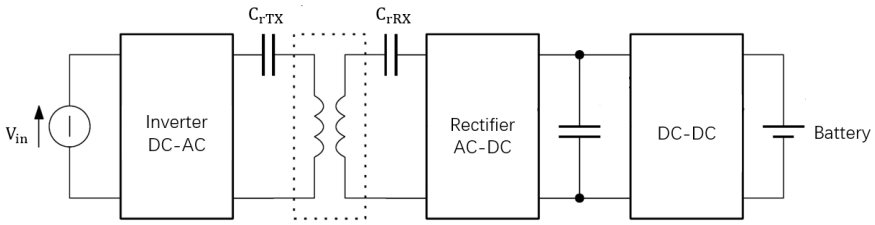


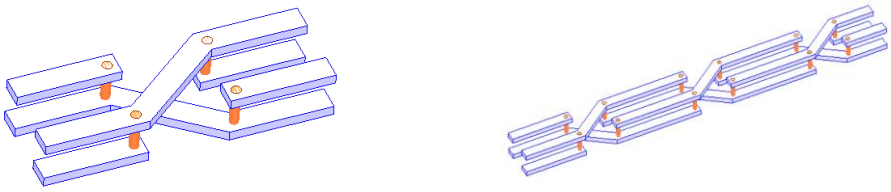
Fig. 5 CLLC model of mobile phone wireless charging. (Picture credit : Original)

To define major sources of loss when charging, all parts in coupling section including mechanical frame are defined as their equivalent inductive components and resistive components on a T-shape network, with certain boundary conditions defined, electrical parameters like inductance and resistivity value are solved, put them into entire CLLC's circuit simulation to rank loss from every contributor, DCR and ACR of Rx coil are ranking top-2 and with remarkable gap from no.3, their counter part of Tx coil is not dominated since more space available in charger to take up 100+ strands litz wire for coil and heat dissipation features.

Therefore, reducing loss from Rx coil keep to be emphasized task for mobile phone wireless charging development, and efforts can be found from both industries and academic organizations.

2.3.1. FPC hybrid coil

Limited by etching and plating process which ends up with non-vertical side surface of copper traces, the thickness of FPC copper foil is hard to be >70um, used to be 40-55um duo to cost consideration, but the thinner conductor could lead to conductive loss, as compensation, width is increased, e.g. to 1mm level, the wide copper trace can be split into 2~4 strands to reduce eddy-current. The magnetic field from interaction between Tx amd Rx are unevenly distributed, stronger at inside and weaker at outside, as consequence, there will be inducted electrical potential difference between adjacent strands within the same turn, the delta will cause circulating current, it adds more loss; a twisting by via hole to interchange inner- and outer position as in Fig.6 (a), which is simulating real litz wire, can cancel out the delta potential between the pair of strands [8-10]. Each turn of copper trace is principally in spiral shape instead of real round circle, in many case it's in more irregular shape duo to space limitation, such the magnetic field is not centrally symmetric, which add more risk for electrical potential difference so as extra loss. A direct solution is to twist frequently as showed in Fig.6 (b) which is a copy from real litz wire, but in practice, to many via hole on FPC is with higher cost and challengeable for process, to say nothing of the imperfection of via hole either geometrically or from quality point of view.



(a) (b)

Fig. 6 real litz wires(a) twisting between adjacent strands; (b) twist frequently to simulate round litz wire's. (Picture credit : Original)

To investigate minimum via quantity, two conditions should be satisfied. 1) within scope of 2 adjacent twist, the induced electrical potential difference between a pair of strands within same turn is smaller enough to be neglected. 2) the loss is non-uniformly distributed among strands. With a example coil of 7 turns, 11 strands and outer diameter 37mm, simulation show that, when all the strands have occupied all possible position 2.54 times along the coil, the different of the following 3 factors between 2 adjacent strand pairs is negligible: the net flux linkage, strand length within 2 adjacent twisting, and magnetic field squared value multiply by the length of the strands [9].

But there still a factor which couldn't be well counted with theorical approach that, dislike traditional round litz wire, in which the twisting is a nature extension of same wire and with only orientation change, the twisting of FPC litz is by via holes, which came from drilling and plating process to form a metalized imperfect vertical path between Cu foil on 2 side of FPC, the end opening occupies big percentage on width of wire trace which add more discontinuity. All these will end up with more loss especially conductive loss. There need be more study or DOE to determine case by case about the balance between add twisting to reduce eddy current loss and reduce via holes to reduce conductive loss. Huawui Mate40's FPC coil is with 4 twists for every turn as in Fig.7(a), and Mate 50 are with much less twists as in Fig.7(b).



(a) (b)

Fig. 7 Huawei phone Rx coil with print marks removed by AI, (a) Mate40; (b)Mate50. (Picture credit : Original)

Comparing to wire winding coil, FPC litz provide flexibility to change width and even shape of conductor trace which can be taken use to minimized loss caused by non-uniformity of magnetic field.

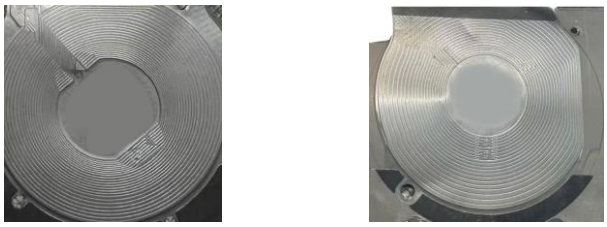
The eddy current loss on FPC copper trace is [8].

$$P_{loss} \approx \frac{lhw^3\sigma\omega^2 B_z^2}{24} \tag{3}$$

Where l, h and w are respectively length, thickness and width of copper trace, σ is conductivity, ω is angular frequency, Z is vertical component of the magnetic flux density. In inner circles of coil where magnetic field is stronger, splitting copper trace into more strands and twist it, can help reduce eddy current from skin effect and proximity effect; in outer circles where magnetic field is weaker, adopt wider trace to reduce conductive loss from DCR, this can also avoid negative affection from via holes.

Validation with 20W charging shows that, comparing to full FPC litz wire, such hybrid solution improves both DCR and charging efficiency; comparing to traditional round litz wire, although DCR increased by nature, there is still 0.77% efficiency increase observed. Huawei mate70 coil shows similar solution, trace width is design with 3 stage, the outer the wider, the inner strands are twisted

as in Fig.8(a). Huawei mate80pro Max coil shows gradual width change from outer wider trace to inner narrower ones and twisting added on inner strands as in Fig.8(b).



(a) (b)

Fig. 8 Huawei phone Rx coil with print mark removed by AI, (a) Mate70; (b)Mate80pro Max. (Picture credit : Original)

Although not all these changes come from technical evolution, there might be IP considerations, while the changes do present the trend of FPC's flexibable pattern design.

2.3.2. FPC coil with identical turns

All the above efforts are to reduce loss under non-uniformally distributed magnetic field, another direction is to improve uniformity of the field, a intuitive solution is letting all coil turns and strands with same length, shape and distribution. In consequence, magnetic field will be centrally symmetric, and all the turns are with identical distribution with respect to the field, the induced current and so does eddy current loss will be minimized. Practically by two layers copper foil, every turn travel between 2 layers by plated via, all turns are with almost same geometry, every turn experiences all possible radial position in same way as in Fig.9 [11].



Fig. 9 one of two strands of a coil by copper foil with identical turns. (Picture credit : Original)

There are still plenty of via holes distributed along inner and outer circle on the above design, the further optimization is to reduce via quantity without introduce more conductor length for lead-out since the lead-out will add DCR.

By now, no study testifies this concept is feasible for Qi compliance charging yet, a obvious question is if 11 turns feasible by this concept, even so the direction of non-uniformlly distributed turns and centrally symmetric magnetic field worth further study at least for non-standard charging, e.g. for small power device like ear piece.

2.3.3. In-parallel and in-serial switchable coil

Current concept of coil had met the requirement all along the charging power increase from 5W, 10W to 25W, if charging power further increased, e.g. for Qi 50W standard which will be released soon, coil loss will increase accordingly, and conductive loss increases more than eddy current loss in conductor and core loss in magnetic material, which cause negative effects on charging efficiency and heat dissipation [12]. If cutting a coil in two, each with roughly half the number of turns of current coils, when connecting them in parallel, both number of turns and resistance will be only half and thus conductive loss will be reduced in large extend, it can be used in high power charging situation. The high power charging phone may reduce it charging power sometimes, e.g. when battery is almost full, or mating to a lower generation charger, then connect the 2 coil in serial, the coil module can still working as current normal way.

There can be 2 topologies to arrange two sub-coil within current coil profile, as show in Fig.10. 1) concentric circles which means one coil contain another one with same spiral center, 2) two coils are wound in parallel, both with similar geometry and experiencing similar magnetic field. In the first one, the 2 coils are with different size and position, so phase mismatching can take place on current, which will increase both eddy current loss and core loss, so the second one is preferable. A test under MPP environmental with both coil in 6.5 turns and rectifier output voltage 19V shows both the above 2 solutions can meet 50W charging requirement, and parallel-winding one is with lower loss than the concentric one.

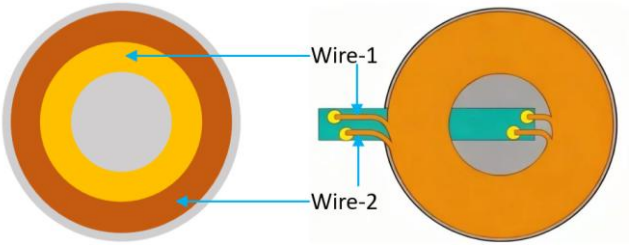


Fig. 10 switchable coil between in-parallel and in-serial. L-concentric, R- in-parallel wounded. (Picture credit : Original)

2.3.4. Wire winding vs FPC

Apple, and Samsung & Huawei keep stay with respectively wounded wire and FPC for Rx coil for years. Wire-winding coil is with advantage of big section area with smaller thickness, and the parallelly wounded strands could reduce eddy current; Apple even use square section wire to further increase its section area as in Fig.11, but the drawback is only same type of wire used and it's need be carefully designed to approach to certain parameter values. FPC have thickness limitation but with flexibility in trace width instead of keeping only same conductor section.



Fig. 11 Left- Iphone 17E's coil by square-section wire vs Right- other coil by round-section wire. (Picture credit : Original)

Now comes the moment WPC will release its Qi 50W standard soon with almost most major phone makers actively involved, and smaller inductor solution will become one of solution of this new standard, it's worth reconsidering new solution for both of wire-winding coil and FPC coil [2]. the breakthrough for wire-winding can be at manufacture side to wind different type of wire into one coil with thickness and flatness well controlled so as to give flexibility for challengeable targets; and for FPC, the direction could be adaptively change trace width with respective to magnetic field and increase conductor thickness without remarkable cost increase.

3. Conclusion

This article reviews main streams solutions and new emerging subjects on Rx coil module of mobile phone wireless charging, including 1) Magnetci attachment, multi-poles magnets may provide advantage over traditional S-N or N-S ones, a N-S-S-N case is testified with stronger magnet field which can service in situation of slim design, or increase attraction force from single piece magnet and reduce magnet quantity for cost saving. 2) Nano-crystal, the magnetic characteristics value measured with classical methodology which is to measure magnetic material itself, may not be accurate enough for design simulation, alternatively, it's suggested to conduct measurement in a

similar magnetic environmental like real application. 3) Rx coil, special studies are concentrated on coil solutions towards reducing conductive and inductive loss, FPC hybrid coil integrated with features like uneven width of Cu trace and FPC litz wire, shows better fit to the non-uniform magnetic field; Aiming at upcoming high-power charging application is a 2 coils reconfigurable design, the 2 coils can be switchable between in-parallel and in-serial connection for higher power and lower power charging respectively. Although constrain for IP infringement risk may block some of the above features from widely adoption, while the advantages of single innovative features may encourage eco-system to develop a alternative one.

It's worth noting that, new emerging application of phone wireless charging is posing new technical challenge, for example, reverse wireless charging, which means mobile phone can work as charger to charg small power accessories, this's not considered in current Qi standard. another example is foldable phone, it could be heavier than normal smart phone and there need be studied about what's best practice for magnetic attachment design to be compatible with such heavier phone. All these new challenges are posing opportunity for technical development.

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