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COMMENTS AND REPLIES

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Mutual Coupling Reduction for a UWB Coplanar Vivaldi Array by a Truncated and Corrugated Slot

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***Abstract*—This letter reports mutual coupling reduction in an ultrawideband coplanar Vivaldi array (CVA) by incorporating truncated and corrugated slot at the border between adjacent elements. An examination of CVAs shows that mutual coupling in the E-plane is more significant than in the H-plane. Subsequently, arrays using exponential and rectangular corrugated slot are compared with those without a slot structure through the simulation of a surface current distribution. A novel exponential corrugated truncated (ECT) structure is implemented to improve a mutual coupling performance, while maintaining or even improving copolar field patterns. The results of simulation and measurement indicate that mutual coupling and return loss performance can be improved by controlling the length of corrugated structure and the distance of the slot structure from the center of the Vivaldi's tapered slot. The CVA achieves bandwidth ratio of 5:1, i.e., from 2 to 10 GHz. The ECT-CVA structure reduces mutual coupling to below −20 dB in a large portion of the whole band, shows 3.9–10.2 dBi gain over the entire band, increases a sidelobe level performance at 4–9 GHz compared to the CVA without slot structure.**

***Index Terms*—Antenna array, corrugated antenna, mutual coupling, Vivaldi antenna.**

I. Introduction

VIVALDI antenna was first proposed by Gibson [1] for large bandwidth and high directivity. Other advantages include ability in realizing a desired gain, beamwidth, and beam scanning, as well as practicability for an arrangement into an array. The minimum bandwidth requirement of 2:1 for an ultrawideband (UWB) antenna [2] can be fulfilled by Vivaldi, which has been used in such applications as void detection inside concrete, wearable communications, and sensing systems [3]–[7]. This letter focuses on the coplanar Vivaldi antenna that gives higher gain and more symmetrical radiation pattern than the antipodal Vivaldi antenna (AVA) [8].

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Attempts have been made to realize Vivaldi with larger bandwidth and minimized dimension [9]–[11]. However, smaller antennas reduce efficiency and hardly yield return loss above 10 dB at lowest frequency. While in an array smaller elements can reduce grating lobe at high frequency, such elements can increase mutual coupling if the spacing is less than half wavelength of its lowest frequency, which in turn degrades radiation pattern and return loss.

Mutual coupling reduction techniques between non-Vivaldi elements have been reported, such as meander line [12], metamaterial [13], and strip wall [14], which are complex, employing either double layer or wall. Radiation pattern improvement by corrugated structure has been reported in [15] and [16], but mutual coupling induced has not been studied. Mutual coupling has been studied for the array of AVAs [17], but a return loss for each element and mutual coupling (given by S_{ij}, where $i \neq j$) have not been researched thoroughly.

A previous study [18] shows that the infinite array of the Vivaldi elements benefits from mutual coupling in terms of larger bandwidth. But some applications might only require finite array, for which mutual coupling and return loss at lower band are problematic. Accordingly, our main contribution is the study of mutual coupling and its reduction by applying various types of slot structure at the border between elements in coplanar Vivaldi arrays (CVAs) with limited number of elements built as continuous patch. The first part of this letter evaluates mutual coupling in such arrays, which demonstrates that mutual coupling in the E-plane is more significant than that in the H-plane, as presented in Section II.

The latter part of this letter discusses mutual coupling reduction in the E-plane for CVA by introducing slot structures at the border between adjacent elements oriented transverse to the direction of surface current, strengthened by corrugation and truncation. We compare arrays with different structures in terms of surface current distribution, return loss, mutual coupling, and copolar and cross-polar field patterns. We also provide equations for a length of the slot structure and its distance to the element's tapered slot that determines mutual coupling and return loss. Simulation using computer simulation technology (CST) and measurement show that arrays with exponential corrugated truncated (ECT) slot performs the best in mutual coupling, gain, and sidelobe level (SLL). This is discussed in Section III, while the overall conclusion is given in Section IV.

II. Mutual Coupling in CVA

The Vivaldi elements are designed as in Fig. 1 on FR4 materials with dielectric constant of 4.6, substrate thickness of 1.6 mm,

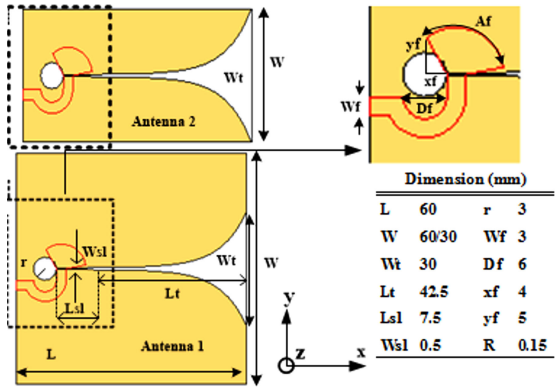

Fig. 1. Dimension of coplanar Vivaldi antenna elements.

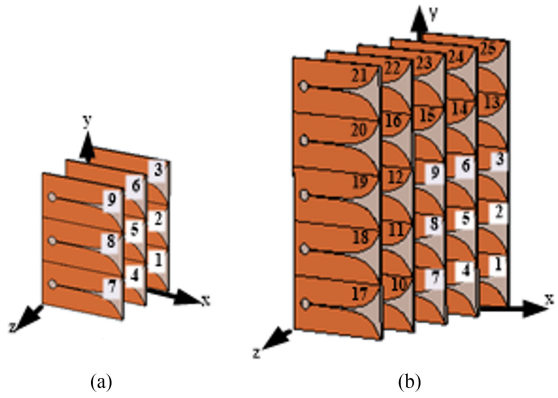

Fig. 2. CVA with dimensions (a) 3 × 3 and (b) 5 × 5, which is an extension from 3 × 3.

and copper thickness of 0.035 mm. The 60 mm × 60 mm element has bandwidth ratio of 5:1, i.e., return loss is better than 10 dB in the 2–10 GHz range, typical of UWB antennas. The tapered slot of Vivaldi can be designed as [17]

$$y = C_1 e^{Rx} + C_2, \quad C_1 = \frac{y_2 - y_1}{e^{Rx_2} - e^{Rx_1}},$$
$$C_2 = \frac{y_1 e^{Rx_2} - y_2 e^{Rx_1}}{e^{Rx_2} - e^{Rx_1}} \tag{1}$$

where y denotes the tapered slot curve, x_1, y_1, x_2, and y_2 the coordinates of the start and end of tapered slot's slope.

CVAs with different dimensions in Fig. 2 are analyzed to get scattering a parameter performance in Figs. 3 and 4 before discussing a mutual coupling method. The center-to-center spacing of 30 mm at 2 GHz for an array structure with continuous patch is equivalent to element width of 0.2 λ_0, but 60 mm is equivalent to element width of 0.4 λ_0. Both antennas have different element widths with other parameters fixed. It yields high mutual coupling ($S_{21} > -10$ dB) around the lower end frequency. Fig. 3(a) and (b) shows S_{11} and S_{21} performance in decibel scale at 2 GHz for element width of 60 mm (0.4 λ) and 30 mm (0.2 λ), respectively. With finite yet increasing number of elements, the array with 30 mm (0.2 λ) element width shows increasing bandwidth as shown by the S_{11} curve in the upper side of Fig. 3(b), but the mutual coupling remains high. Smaller elements with narrower radiator patch and narrower mouth opening of tapered slot

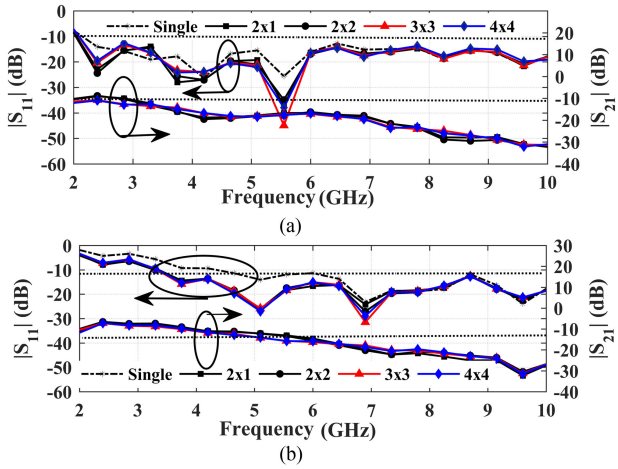

Fig. 3. S_{11} and S_{21} performance of arrays with (a) 0.4 λ × 0.4 λ elements and (b) 0.2 λ × 0.4 λ elements.

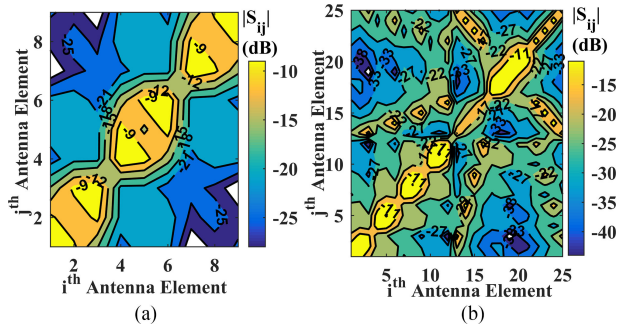

Fig. 4. Contour plot of scattering parameter (S*ij*) for *j*th element to *i*th element for (a) 3 × 3 array and (b) 5 × 5 array, respectively.

shifts upward the lower bound of operating frequency range at which S_{11} is below −10 dB. To obtain low return loss, a Vivaldi antenna is usually designed with slot width of one wavelength [19]. For smaller element width, if the number of elements in the array is gradually increasing to infinity, the bandwidth increases because of a coupling environment. However, in Fig. 2, those arrays are just simulated with the finite number of elements, and therefore, the lowest frequency is still high. In contrast, in Fig. 3(a), for arrays with 60 mm (0.4 λ) element width, the bandwidth does not increase significantly with more elements. Smaller spacing between feeding points in the E-plane changes the coupling environment so that anomalies of impedance occur. However, the increasing number of element can increase the bandwidth.

The *S*-parameters at 2.4 GHz of 3 × 3 arrays in Fig. 4(a) and 5 × 5 arrays in Fig. 4(b) are shown in contour plots for element width of 0.2 λ with the numbering of antenna element is the same as a port number of the antenna given in Fig. 2. They reveal that increasing number of elements enhances the performance of a return loss as well as a mutual coupling parameter. It can be seen for the 3 × 3 array, S_{33} is −9 dB, while the 5 × 5 array has S_{33} of −11 dB. For the 3 × 3 array, S_{98} is −9 dB but for the 5 × 5 array, S_{98} is −11 dB, where S_{ij} for $i \neq j$ is the coupling from *j*th element to *i*th element for an arrangement shown in Fig. 2. By increasing the number of elements, mutual scattering can be reduced because it is induced by coupling from elements on

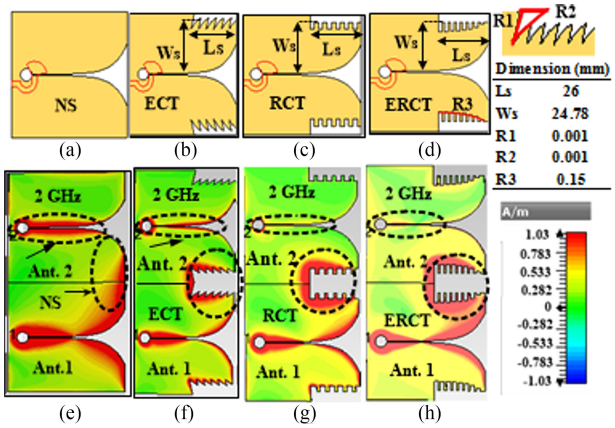

Fig. 5. Geometry of the Vivaldi element with slot structures. (a) NS, (b) ECT, (c) RCT, and (d) ERCT with their corresponding current distribution in (e)–(h).

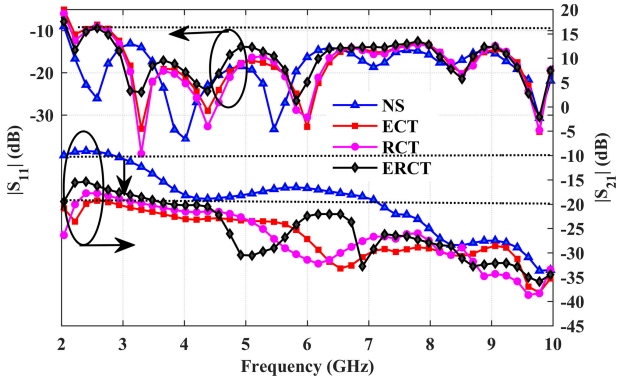

Fig. 6. *S*-parameters for arrays with various structures.

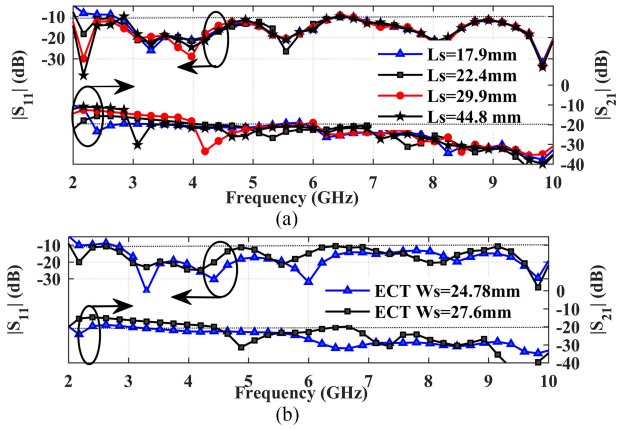

Fig. 7. *S*-parameters. (a) Varying *Ls*. (b) Varying *Ws*.

all sides. In the E-plane, mutual coupling appears to be larger than it is in the H-plane. For the 5×5 array, in the E-plane, S_{56} is around -11 dB, which is higher than mutual coupling in the H-plane with S_{58} of around -22 dB. In the E-plane, surface current flows in the adjacent element, which causes coupling between elements, whereas in the H-plane, coupling is induced by electric field through the air. The diagonal of contour plot shows $S_{ij} = S_{ji}$. Over all, these observations indicate that mutual coupling is a bigger issue than return loss in CVAs, with greater impact shown in the E-plane than the H-plane.

III. Mutual Coupling Reduction

A. Vivaldi Antenna and Surface Current Performance

We consider several slot structures, i.e., straight, exponential, corrugated and truncated, or their combinations. Truncated slot has been used in [18] but how it reduces mutual coupling is not explained. Corrugated slots have been used in [15] and [16] for different purposes to improve radiation pattern, as well as in our previous work [20]. Aside from no slot structure (NS), there are three types of slot structure evaluated herein for mutual coupling reduction, as shown in Fig. 5, namely, ECT slot, rectangular corrugated truncated slot (RCT), and exponential RCT slot (ERCT). All structures are simulated with the same amplitude excitation with ideal (lossless) power divider connected to SubMiniature version A (SMA) connectors.

B. Surface Current Performance

Fig. 5 shows geometry of coplanar Vivaldi element and surface current in two element array when the lower antenna (antenna 1) is excited and the upper (antenna 2) is terminated at 2 GHz. Surface currents in NS array in Fig. 5(e) couple to the upper antenna, which is observable from the direction of the surface current in the areas encircled. This happens because there is no transverse structure in between the elements that disturbs the flow of the leaking surface current. In contrast, surface current on array with ECT in Fig. 5(f), RCT in Fig. 5(g), ERCT in Fig. 5(h), concentrated along the slot structure at the border, thus, reducing the current that flows to the next element. To further enhance the current concentration around the slot structure and minimize the leakage, saw tooth corrugation can be applied to the slot, for which higher corrugated slope gives better result. In the corrugated slot, surface currents propagate to adjacent element along a longer path than in the straight structure and also crash each other, thereby increasing isolation.

C. Scattering Parameter Performance

Fig. 6 compares S_{11} and S_{21} of Vivaldi arrays with various slot structures. The array structures in the order of superiority in S_{11} performance at 2.2 GHz are ERCT, RCT, ECT, and NS. Better isolation is achieved with ECT, RCT, ERCT, and NS in the descending order of superiority at around 4 GHz. The best isolation is achieved for ECT. Accordingly, it suggests that corrugated structure should be used with truncation for the isolation.

Increasing L_s with a constant $W_s = 0.5\,\lambda_g$ (at 4 GHz) can improve return loss performance but reduce isolation as shown in Fig. 7(a). Longer L_s makes surface current spread along truncated slot over longer path and subsequently make the U-turn. Some of the surface current directly flows towards the area in the beginning of tapered slot in the adjacent element and reduces isolation. In contrast, the shorter corrugated truncated slot makes some of surface current spread near opening of tapered slot in the excited element and escalates return loss at lower frequency. After the surface current makes a U-turn to the next element, it flows to the center slot with longer trajectory that enhances isolation. S_{11} performance below -10 dB can be reached from 2 to 10 GHz by setting the length of L_s

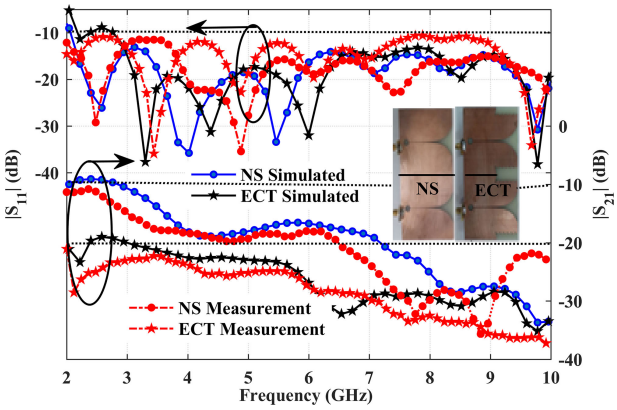

Fig. 8. Simulation and measurement S_{11} and S_{21}: NS and ECT.

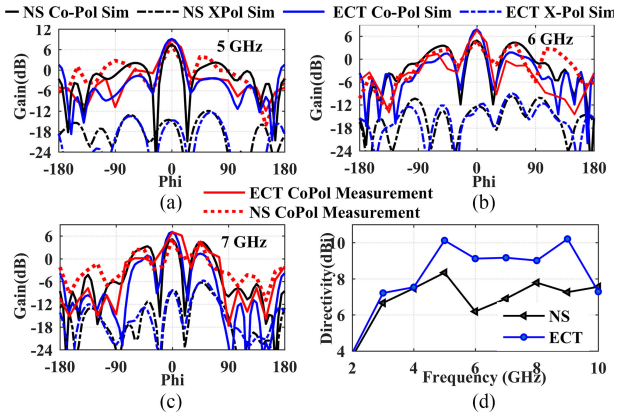

Fig. 9. Simulation and measurement results of copolar gain and simulation of cross-polar gain in the E-plane at (a) 5 GHz, (b) 6 GHz, and (c) 7 GHz. (d) Directivity at 2–10 GHz for ECT and NS.

to $0.5\,\lambda_g$ with guided wavelength λ_g obtained from any value of f (GHz) where $f_L \leq f \leq (f_c - 2)$ and setting W_s to $0.5\,\lambda_g$ where $f_L + 1 < f < (f_c - 2)$, with f_L and f_c is the lowest and the center frequency, respectively. This step gives the rule for minimum and maximum dimensions of L_s and W_s as shown in Fig. 5. By considering effective dielectric [16], the value of L_s and W_s should be set as

$$L_s \text{ or } W_s = 0.5\lambda_g = \frac{c}{2f\left(\sqrt{\varepsilon_{eff}}\right)} = \frac{\sqrt{2}\lambda}{2\sqrt{\varepsilon_r + 1}}. \quad (2)$$

S_{11} and S_{21} for ECT with different values of W_s with a constant $L_s = 0.5\,\lambda_g$ (at 3.5 GHz) are shown in Fig. 7(b). Smaller W_s appears to reduce a return loss performance but leads to higher isolation in both structures. To comply return loss requirement with smaller W_s, larger L_s can be used. Results of simulation and measurement of S_{11} and S_{21} for array with ECT and NS are presented in Fig. 8. By simulation, at 2.16 GHz, the arrays without slot yield S_{21} of -9.34 dB, whereas those with ECT give S_{21} of -24.19 dB. It is found that both simulation and measurement show consistency.

D. Radiation Pattern Performance

Fig. 9 compares simulation and measurement (see Fig. 10) results of a copolar gain and simulation of a cross-polar field

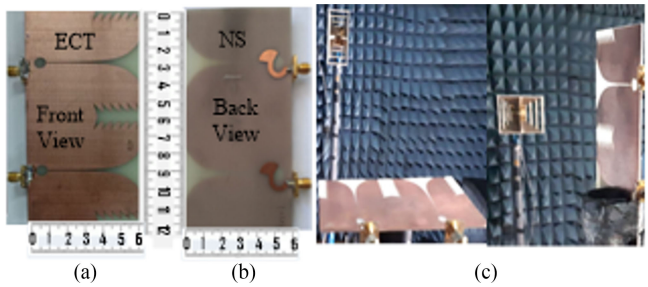

Fig. 10. Fabricated antenna. (a) ECT, (b) NS, and (c) ECT measurement.

TABLE I
COMPARISON OF ECT AND NS ARRAYS

f	Dir (dBi)		Co-Pol (dB)		X-Pol (dB)		SLL(dB)		$\lvert S_{21}\rvert$(dB)	
(GHz)	ECT	NS	ECT	NS	ECT	NS	ECT	NS	ECT	NS
2	3.9	3.7	3.5	3.3	-26	-22	-7.2	-7.2	-20	-9.8
3	7.2	6.7	6.8	6	-17	-15	-7.8	-8.7	-16	-11
4	7.5	7.5	6.8	6.7	-15	-14	-6.3	-5.3	-18	-18
5	10.1	8.3	9.1	7.4	-12	-12	-7.5	-5.3	-29	-18
6	9.1	6.2	7.8	4.8	-9	-9	-6	-1.6	-23	-17
7	9.2	6.9	7.1	5.1	-5.7	-6	-5.8	-2.1	-29	-19
8	9	7.8	6.6	5.8	-4	-4	-3.3	-2.8	-27	-25
9	10.2	7.3	7.1	4.9	-2.5	-3	-6.9	-1.2	-30	-28
10	7.3	6.6	0.7	-0.5	3.8	3	-1.6	-1	-34	-33

pattern in the E-plane between ECT-CVA and NS-CVA. The arrays generally preserve the wideband directivity as shown in Fig. 9(d). Radiation pattern and S_{21} performance of arrays with ECT and NS at various frequencies are shown in Table I. Directivity, copolar gain and S_{21} of ECT-CVA is better than NS over the whole band of 2–10 GHz, whereas the cross-polar gain for ECT is better than NS in the lower end frequency. ECT only improves SLL at 4–9 GHz, while at 10 GHz, array with element width of 60 mm has center-to-center spacing of $2\,\lambda_0$, which yields grating lobes. A corrugated slot in antenna focuses electric field and enhances surface current over the whole patch, thus, improving directivity and radiation pattern. There are tradeoff between return loss, isolation, and SLL performance in an UWB antenna, which is influenced by the geometry of the antenna, feeding shape, patch design, and substrate.

IV. CONCLUSION

We have found that mutual coupling in UWB-CVA is more prevalent in E-plane than in H-plane. A family of mutual coupling reduction methods for CVA with various slot structures at the edges of adjacent elements has subsequently been demonstrated. Generally, the reduction of mutual coupling is achieved by placing a slot structure transverse to the direction of surface current at the border between elements to reduce surface current flowing to the next. The ECT structure is effective to improve isolation in all bands, especially at lower frequency, directivity in the whole band of 2–10 GHz, and SLL in 4–9 GHz. Therefore, it can be applied for the UWB CVA antenna application.

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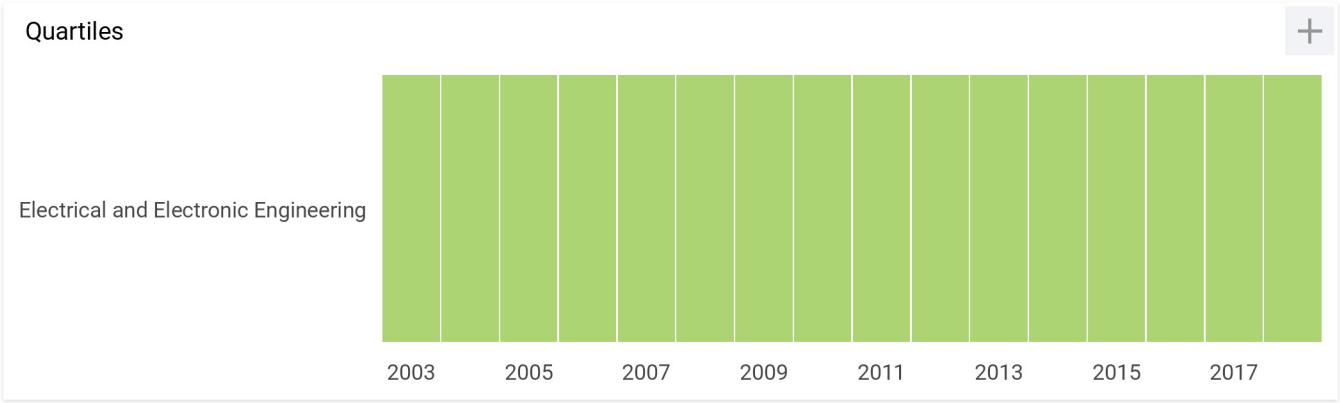

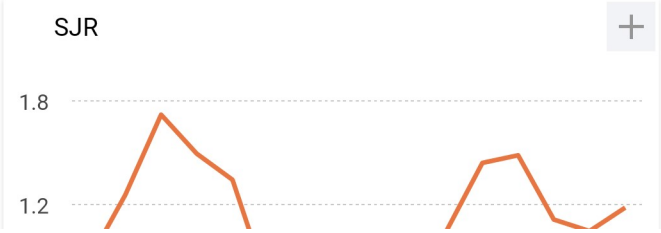

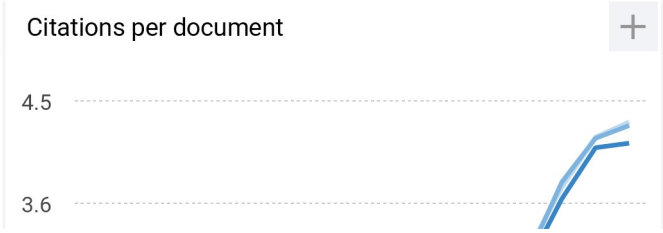

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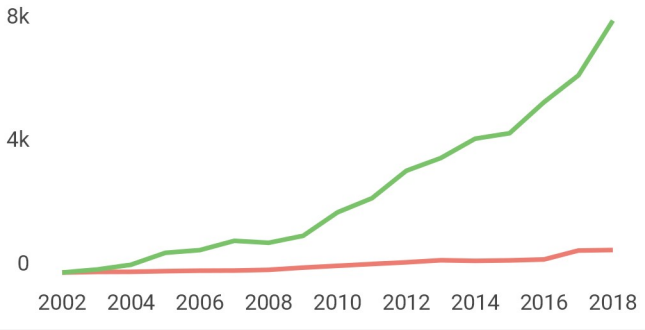

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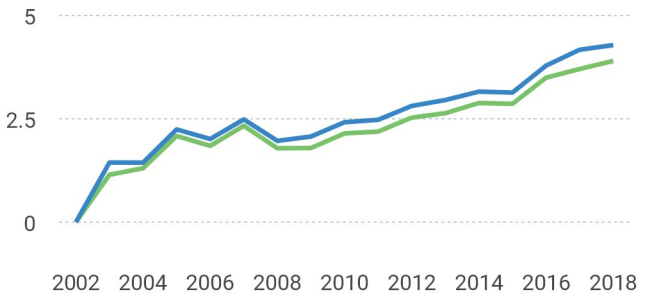

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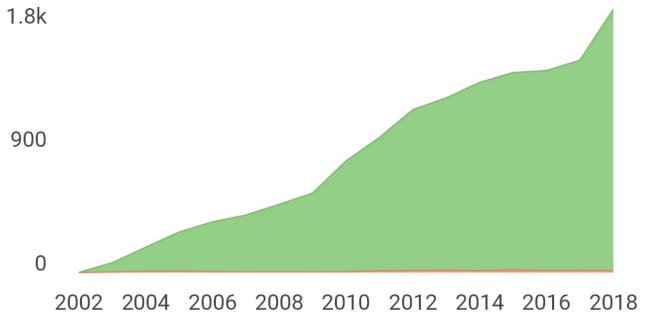

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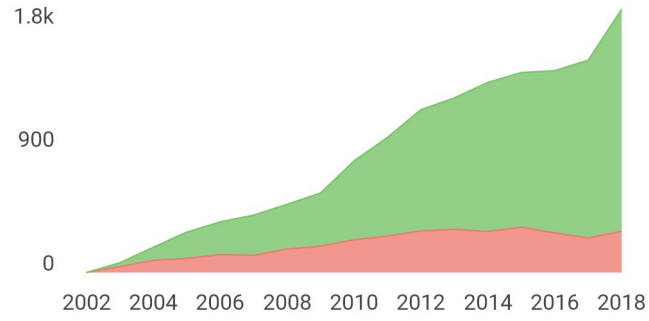

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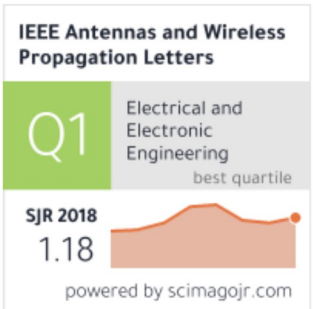

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