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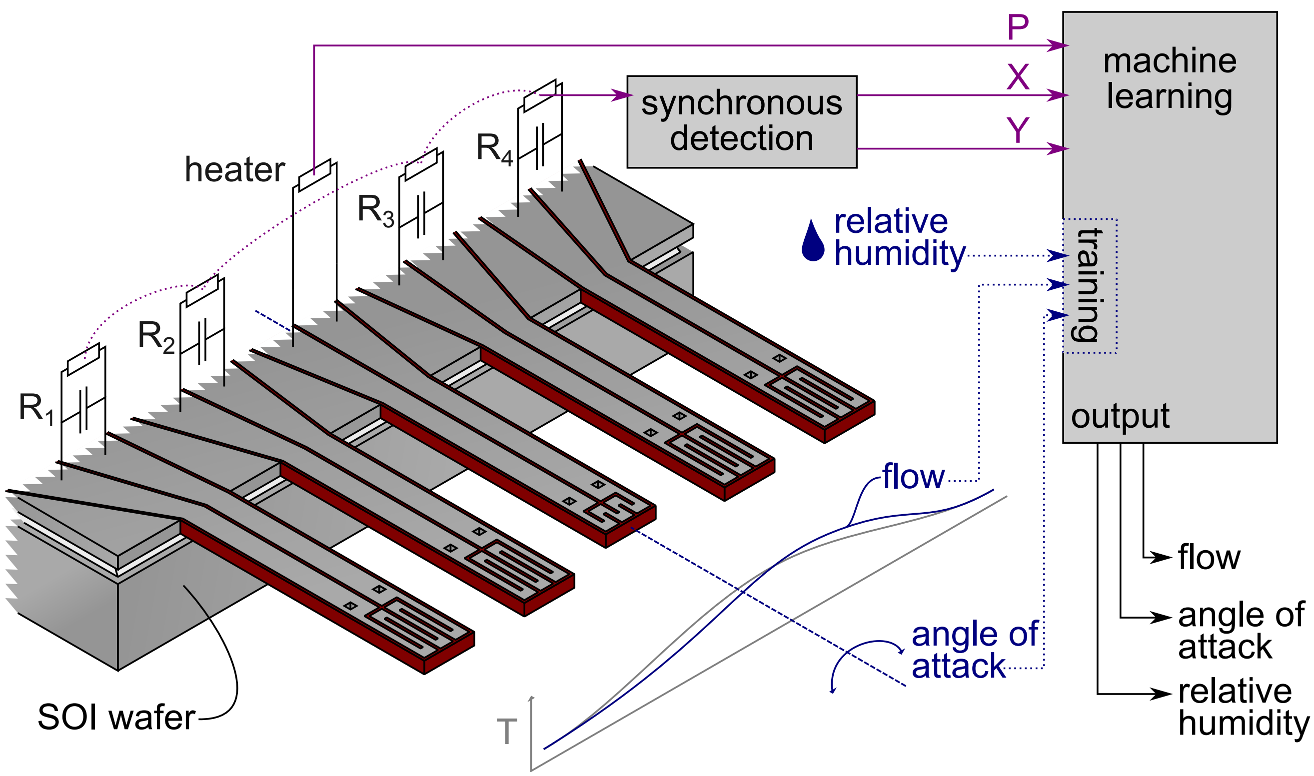

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Microwave/millimeter wave sensors

Collaboratively Far-Field and Near-Field Regions for Dual-Modalities Microwave Permittivity Sensor Using T-Shaped Resonator Embedded With IDC

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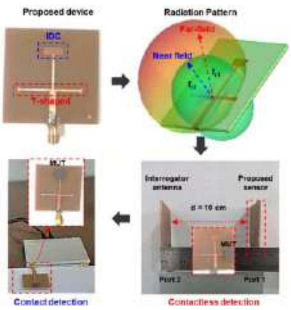

Abstract—This letter introduces collaboratively far-field and near-field regions for dual-modalities permittivity sensor to characterized solid materials. The proposed sensor comprises a T-shaped resonator featuring a single port embedded with interdigital capacitor (IDC). The first resonator, operating at $f_{r1} = 2.43$ GHz as the long-distance detection, utilizes the far-field region, while the second resonator, working at $f_{r2} = 1.64$ GHz, functions as the contact detection, utilizes the near-field region. These resonators possess distinct sensing hotspots, enabling independent utilization. Contact detection is achieved by utilizing the near-field region by placing the material under test (MUT) directly above the surface of the second resonator, while the first resonator for long-distance detection utilized the far-field region by using the interrogator antenna at a distance of d = 10 cm. The experimental results demonstrate that the proposed sensors exhibit a maximum sensitivity of 5.13% and 3.40% for near-field and far-field detections, respectively. Moreover, the average accuracy for both contact and long-distance detections is 95.99% and 95.16%, respectively, when compared to the permittivity values obtained from the datasheet within the range of 1–6.15. This research holds significant practical value for the contact and long-distance characterizations of solid materials, particularly in applications, such as biomedical, quality control, and pharmaceutical industries.

Index Terms—Microwave/millimeter wave sensors, dual modalities, far field, microwave sensor, near field, solid materials.

I. INTRODUCTION

Microwave sensors (MS) have gained widespread development for assessing both solids and liquids due to their benefits, including high precision, a high Q-Factor, affordability, and compact size [1]. One of the properties they can detect is permittivity, which refers to a material's capacity to retain an electric field. Moreover, permittivity of the material under test (MUT) can be ascertained through perturbation theory, assuming that the MUT acts as a capacitive load [2]. Previous studies have put forth various MS employing resonators, such as split ring resonator (SRR) [3], complementary SRR [4], substrate-integrated waveguide [5], and interdigital capacitor (IDC) [6] for assessing solid substances. In contrast, previous work proposed by Alam et al. [7] introduces a dual T-shaped resonator featuring a single port for characterizing solid materials with contact and noncontact. However, this work has disadvantages, such as a very limited distance of 0.5–1.5 mm for noncontact detection, poor sensitivity, and the fact that the locations of the E-field and H-field are ambiguous. Another work, presented in [8], suggests a multifunctional dual-band MS with an antenna for communication purposes. However, the MUT's characterization is only performed directly by placing it on the sensing hotspot. In addition, the authors in [9] and [10] employed an antenna as a permittivity sensor for contactless detection at a distance of 20 and 30 mm using artificial magnetic conductor. However, the proposed sensor features only one sensing hotspot and therefore cannot facilitate contact and long-distance characterizations independently. Therefore, several requirements are needed to obtain high-performance MS with long-distance detection, high sensitivity, clear location between E-field and H-field, and dual hotspot location for contact and long distance.

To fulfill this requirement, this letter introduces a collaboration between near-field and far-field regions for microwave permittivity sensors operating at two resonant frequencies. In detail, the main contribution of this research, such as the proposed long-distance detection MS with two independent sensing hotspots, enables contact and long-distance characterizations of solid materials. To obtain a clear location between E-field and H-field with high sensitivity performance, a T-shaped resonator embedded with IDC was proposed. The first resonator operates at $f_{r1} = 2.43$ GHz for long-distance detection and the second resonator operates at $f_{r2} = 1.64$ GHz for contact detection. Furthermore, near-field and far-field regions for permittivity detection are determined based on S_{11} and the radiation pattern of the two

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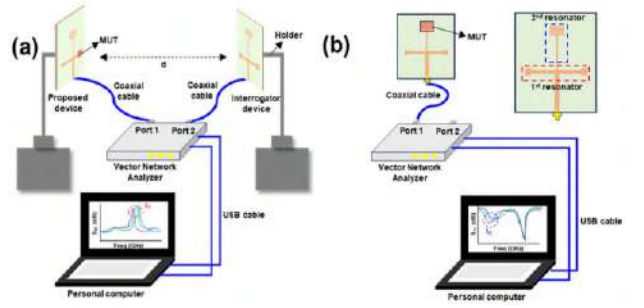

Fig. 1. Scenario of permittivity detection using proposed sensor. (a) Scenario (1) for long-distance detection using an interrogator antenna. (b) Scenario (2) for contact detection.

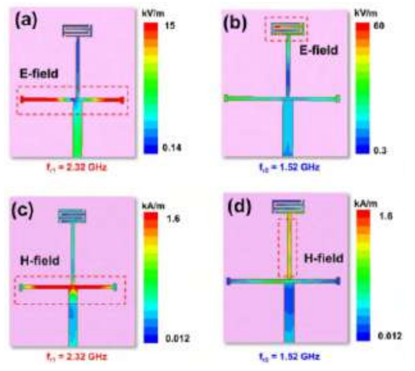

Fig. 2. (a) E-field at f_{r1}. (b) E-field at f_{r2}. (c) H-field at f_{r1}. (d) H-field at f_{r2}.

resonators, while for distance of (d), refer to Fresnel region with $d \geq \frac{2D^2}{\lambda}$ [11].

II. SENSOR DESIGN

A. Scenario of Near-Field and Far Field Regions for Characterization of Solid Materials

In this letter, two scenarios are proposed for far-field and near-field regions for the characterization of solid materials using the proposed sensor, as shown in Fig. 1(a) and (b), with the following explanation.

1) Furthermore, scenario (1) proposes long-distance detection using interrogator antennas operating at the same resonance frequency as the first resonator at f_{r1}= 2.32 GHz with $S_{11} \leq -10$ dB and separated by distance (d) of 10 cm. Long-distance permittivity detection is carried out by observing changes in the resonant frequency based on S_{21}, as shown in Fig. 1(a).
2) For scenario (2), near-field region for contact detection is proposed by placing the MUT on the IDC of the second resonator operating at f_{r2}= 1.52 GHz with $S_{11} \geq -10$ dB by observing changes in the resonant frequency based on S_{11}, as shown in Fig. 1(b).

The location of the sensing hotspot is determined based on the concentration of the E-field and H-field of the proposed resonator. The surface of the resonator with high E-field can be used to detect the permittivity of MUT. The E-field and H-field concentrations of the resonator are shown in Fig. 2(a)–(d).

Fig. 2(a) and (c) shows that the high E-field and H-field concentrations at $f_{r1} = 2.32$ GHz are at the same location on the arms of the first resonator. Other findings, as shown in Fig. 2(b) and (d), show that the highest E-field is in the gap of the IDC while the H-field is

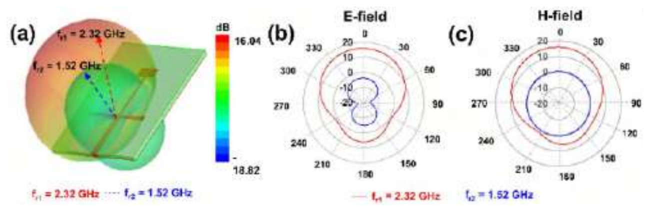

Fig. 3. (a) Radiation pattern of the proposed resonator at $f_{r1} = 2.32$ GHz and $f_{r2} = 1.52$ GHz. (b) E-field at $f_{r1} = 2.32$ GHz and $f_{r2} = 1.52$ GHz. (c) H-field at $f_{r1} = 2.32$ GHz and $f_{r2} = 1.52$ GHz.

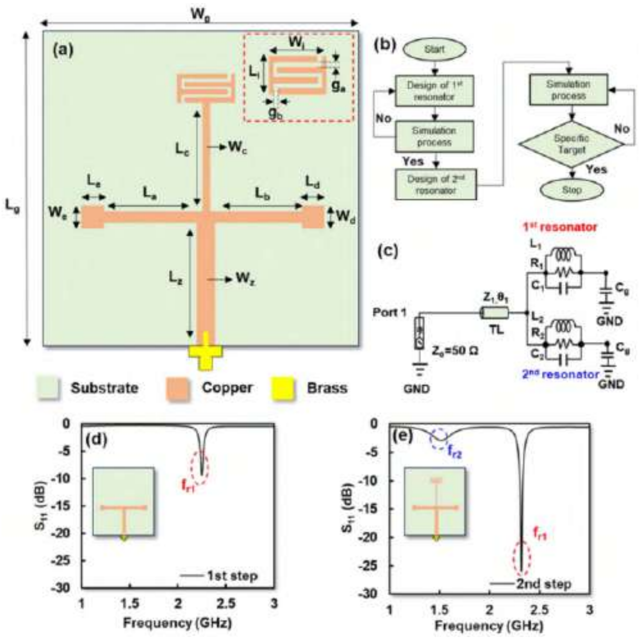

Fig. 4. (a) Structure of T-shaped resonator. (b) Flowchart of design process. (c) Equivalent circuit. (d) First step model. (e) Second step model.

in the arm of the second resonator. Furthermore, simulations of the radiation patterns at $f_{r1} = 2.32$ GHz and $f_{r2} = 1.52$ GHz are shown in Fig. 3(a)–(c).

Fig. 3(a) shows that the radiation pattern at $f_{r1} = 2.32$ GHz is higher than $f_{r2} = 1.52$ GHz. This finding is also in line with the simulations of E-field and H-field radiations shown in Fig. 3(b) and (c), respectively. This shows that resonators with high radiation can be used for long-distance detection by utilizing the far-field region, while low radiation can be used for contact detection by utilizing the near-field region.

B. Structure of Proposed Sensor

The dual modalities sensor is constructed utilizing of FR-4 substrate with specific properties: a dielectric constant (ε_r) of 4.3, a loss tangent (tan δ) of 0.0265, and a thickness (h) of 1.6 mm.

The configuration of T-shaped resonator and IDC can be observed in Fig. 4(a). Detailed dimensions of the proposed T-shaped resonator can be described as follows: $W_z = 3$ mm, $L_z = 17$ mm, $L_a = 16$ mm, $L_b = 12.5$ mm, $L_c = 18$ mm, $L_d = L_e = 1$ mm, $W_d = W_e = 2$ mm, and $W_g = L_g$ 50 mm, while for IDC represented by $W_i = 9.5$ mm, $L_i = 3.5$ mm, and $g_a = g_b = 1$ mm. Moreover, the flowchart of the design process dual T-shaped resonator is presented in Fig. 4(b) while for equivalent circuit shown in Fig. 4(c). In the initial phase, the resonator functions at $f_{r1} = 2.32$ GHz, as shown in Fig. 4(d), while in the subsequent phase,

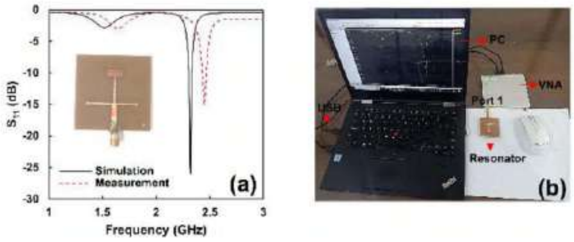

Fig. 5. (a) Comparison simulation and measurement result of proposed resonator. (b) Measurement setup of proposed resonator.

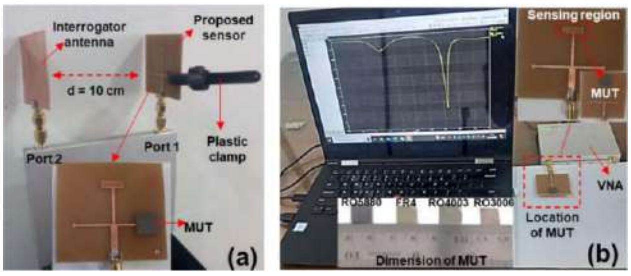

Fig. 6. Measurement setup. (a) Long-distance detection using scenario (1). (b) Contact detection using scenario (2).

it operates at a dual-band resonant frequency, with $f_{r1} = 2.32$ GHz and $f_{r2} = 1.52$ GHz, as shown in Fig. 4(e), respectively.

III. MEASUREMENT AND VALIDATION

A. Measurement of Proposed Sensor

Furthermore, Fig. 5(a) demonstrates that the measurement setup while the outcomes are consistent and exhibit dual-band characteristics in accordance with the simulated results, as shown in Fig. 5(b). Nonetheless, there is a slight deviation in the resonant frequencies of the resonator. Specifically, f_{r1} shifts from 2.32 to 2.43 GHz, with S_{11} of −15.05 dB, and f_{r2} shifts from 1.52 to 1.64 GHz, with S_{11} of −3.01 dB. This discrepancy can be attributed to minor variations in the fabrication process and inherent fluctuations in the permittivity of the FR-4 substrate, ranging from 3.8 to 4.8 [12].

B. Experimental Validation

The experimental validation was conducted utilizing a vector network analyzer spanning a frequency range of 1–3 GHz, with a frequency sweep increment of 0.01 GHz. The ambient temperature during the measurements was maintained at 25 °C. In addition, four distinct materials with known permittivity were employed as MUT: RO5880 possessing a permittivity of 2.20, RO4003 of 3.65, FR-4 of 4.30, and RO3006 of 6.15 with the dimension of MUT is $10 \times 10 \times 1.6$ mm^3. Moreover, to ensure that the location of the MUT is constant, we carefully place the MUT at the location of the sensing hotspot using plastic clamp, which is for contact detection on the surface of the IDC and for long-distance detection on the surface of the T-shaped resonator, as shown in Fig. 6(a) and (b). Furthermore, Fig. 7(a) shows that f_{r1} shifts to low frequency in line with the increased permittivity of the MUT placed at the sensing hotspot of the first resonator for long-distance detection with d = 10 cm, while f_{r2} is fixed. The resonant frequency of the first resonator shifted from 2.43 to 2.35 GHz with a permittivity range of 1–6.15, as shown in Fig. 7(c).

In the other hand, Fig. 7(b) shows the performance of the proposed sensor for contact detection. It is evident that f_{r2} experiences a downward shift in resonant frequency, corresponding to the increased permittivity of the MUT positioned on the sensing hotspot of the second resonator, whereas f_{r1} remains constant. Moreover, Fig. 7(d) shows that f_{r1} shifted to the lower frequency from 1.64 to 1.56 GHz in line with the increased permittivity of the MUT placed on the first resonator, while f_{r2} was fixed for permittivity range of 1–6.15.

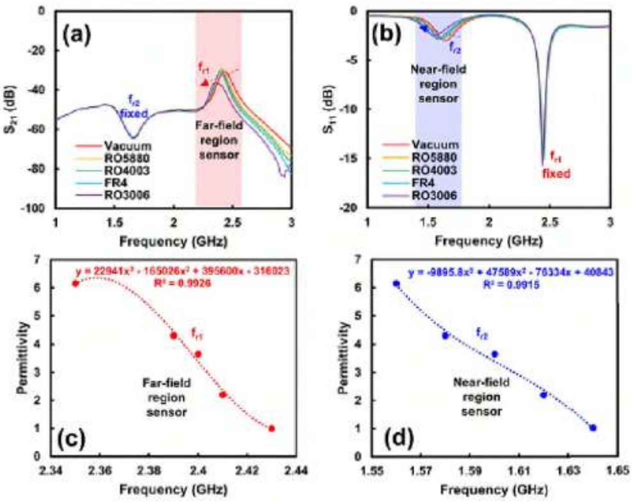

Fig. 7. Permittivity detection using proposed sensor. (a) Long-distance detection with d = 10 cm. (b) Contact detection. (c) Polynomial equation for long-distance detection. (d) Polynomial equation for contact detection.

TABLE 1. Performance of Proposed Sensor

MUT	ε_r ref	Δf (GHz / $\Delta\varepsilon_r$)		Sensitivity (%)		Accuracy (%)	
		f_{r1}	f_{r2}	f_{r1}	f_{r2}	f_{r1}	f_{r2}
Vacuum	1.00	0	0	-	-	97.91	95.64
RO5880	2.20	0.02	0.02	0.83	1.23	92.38	92.08
RO4003	3.65	0.03	0.04	1.25	2.50	92.65	92.84
FR4	4.30	0.04	0.06	1.67	3.80	97.08	95.95
RO3006	6.15	0.08	0.08	3.40	5.13	99.93	99.29

C. Sensitivity and Accuracy of Proposed Sensor

The sensitivity of the microwave sensor is determined from the shift in the resonant frequency when the MUT is placed on the sensing hotspot. The frequency shift is represented as Δf, which shows the difference between the loaded and unloaded frequencies of the resonator. The frequency shift (Δf), sensitivity (S), and frequency detection resolution (FDR) of the microwave sensor can be determined using the following [13], [14]:

$$\Delta f = (f_{\text{unloaded}} - f_{\text{loaded}})\ \text{GHz} \quad (1)$$

$$S = \left(\frac{f_{\text{unloaded}} - f_{\text{loaded}}}{f_{\text{unloaded}}}\right)\% \quad (2)$$

$$\text{FDR} = \frac{\Delta F}{\Delta \varepsilon_r} \quad (3)$$

where Δf represents frequency shift in Gigahertz, S represents the sensitivity of the sensor in percentage, f_{unloaded} represents the resonance frequency of the resonator before being loaded by the MUT, and f_{loaded} represents the frequency of the resonator when it is loaded with an MUT. In this letter, the f_{unloaded} used is when the resonator with

TABLE 2. Comparison With Previous Work

Ref	f_r (GHz)	Range of ε_r	Dimension (mm)		Num. of sensing hotspot	d (mm)	FDR (GHz)	S (%) / Q-factor	Separated E and H fields	Contact /long-distance detection
			Sensor	Sample						
[7]	1.81/2.34	1–6.15	50 × 50	10 × 10 × 1.6	2	1.5	0.023/0.003	2.30/117	No	Yes/No
[8]	1.50/2.00/2.45	1–6.15	50 × 50	10 × 10 × 1.6	2	0.0	0.013/0.027	2.71/120	No	Yes/No
[9]	6.90	1–15	40 × 40	10 × 10 × 4	1	20	0.038	3.80/69	No	No/Yes
[10]	4.04	2–4	30 × 30	25 × 25 × 2.1	1	30	NA	1.89/268	No	No/Yes
T.W.	1.64/2.43	1–6.15	50 × 50	10 × 10 × 1.6	2	100	0.016/0.016	5.13/121	Yes	Yes/Yes

permittivity of vacuum $\varepsilon_r = 1$. Based on the calculations using (1) and (2) shows that the maximum Δf of the first and second resonators has the same value of 0.08 GHz $/\Delta\varepsilon_r$ while the average sensitivities are 1.43% and 2.53%, respectively. The permittivity of the MUT is extracted using a polynomial equation obtained from the shift in the resonant frequency of the resonator, as shown in Fig. 7(b) and (d). Therefore, the permittivity of the MUT for both detections can be determined using the following:

$$\varepsilon_{r1} = 22941 f_{r1}{}^{3} - 165026\, f_{r1}{}^{2} + 395600 f_{r1} - 316023 \quad (4)$$

$$\varepsilon_{r2} = -9895.8 f_{r2}{}^{3} + 47589\, f_{r2}{}^{2} - 76334 f_{r2} + 40843 \quad (5)$$

where f_{r1} is the resonant frequency of the first resonator, and ε_{r1} is the permittivity of the MUT used for long-distance detection, while f_{r2} is the resonant frequency of the second resonator and ε_{r2} is the permittivity of the MUT used for contact detection. The overall performance of the proposed sensors both for long distance and contact detections are given in Table 1.

Moreover, FDR of the proposed sensor based on (3) for f_{r1} and f_{r2} are 0.016 GHz. Table 2 tabulates that the MS has novel dual modalities for contact and long-distance detection by utilizing the near-field and far-field regions with a high sensitivity of 5.13%, long-distance detection with d = 100 mm, and maximum Q-factor of 121 for solid materials with a permittivity range of 1–6.15 and two different sensing hotspots, compared with previous work, which only supports contact or long-distance detection and limited distance for long-distance detection.

IV. CONCLUSION

In this letter, dual modalities microwave sensor for long-distance and contact detections by utilizing the far-field and near-field regions has been successfully designed and realized. The MS consists of T-shaped resonators embedded with IDC operating at f_{r1} = 2.43 GHz and f_{r2} = 1.64 GHz with different sensing hotspots and have independent characteristics. From the measurement results, a maximum sensitivity of 3.40% and 5.13% was obtained for long-distance detection using the interrogator antenna with a distance (d) = 10 cm and contact detection. Furthermore, the average accuracy of the first and second resonators is 95.99% and 95.16%, respectively. The proposed sensor can be a promising solution and can be recommended for contact and long-distance characterization of solid materials for biomedical, pharmaceutical, and quality control industries.

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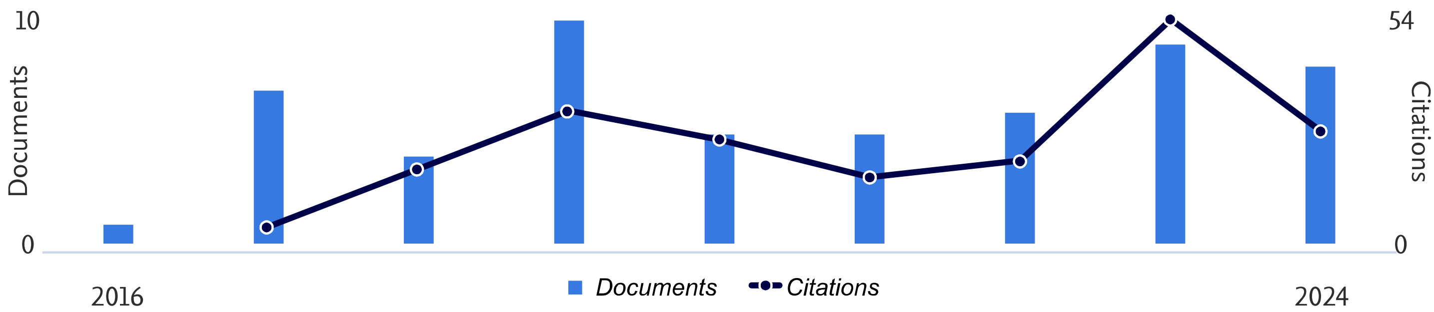

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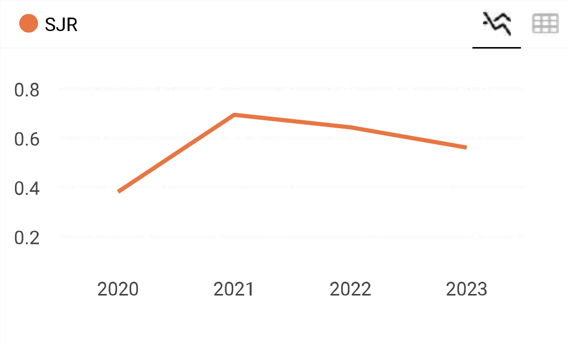
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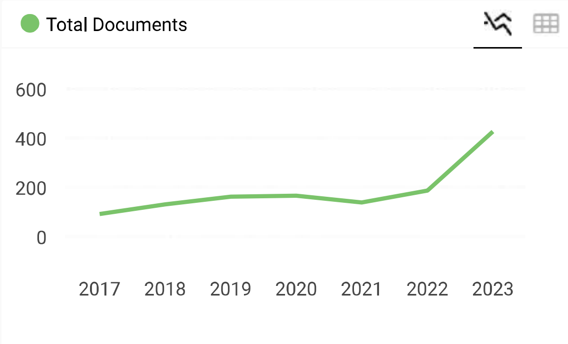
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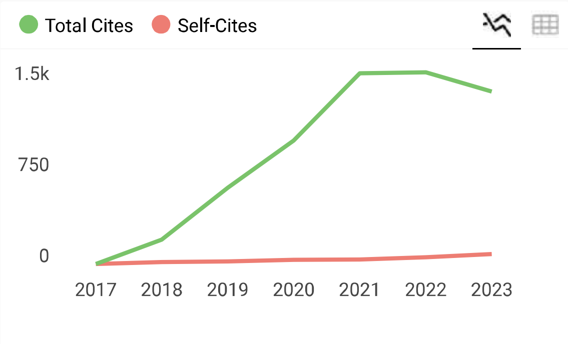
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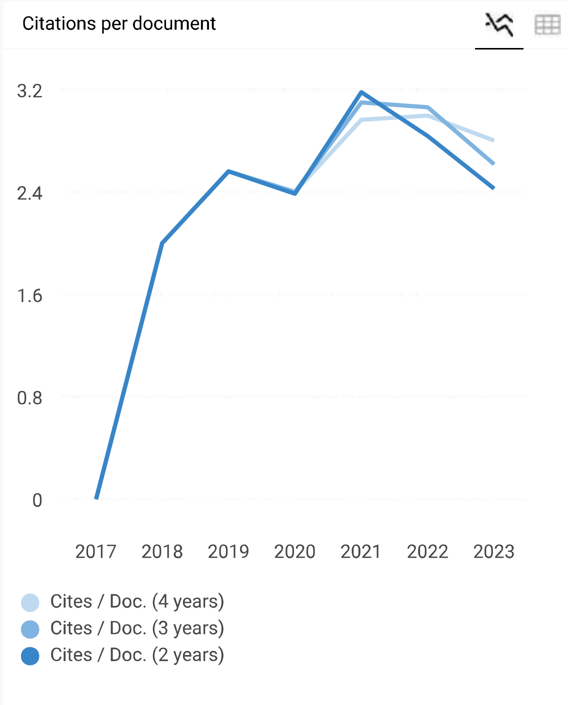
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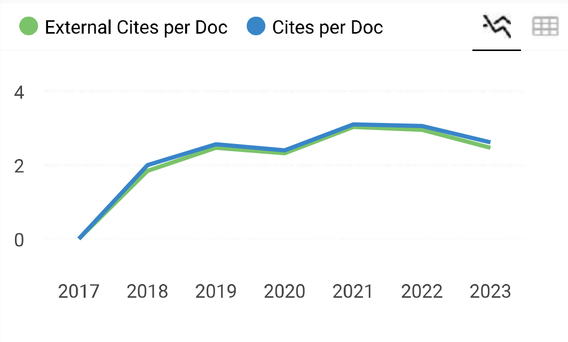
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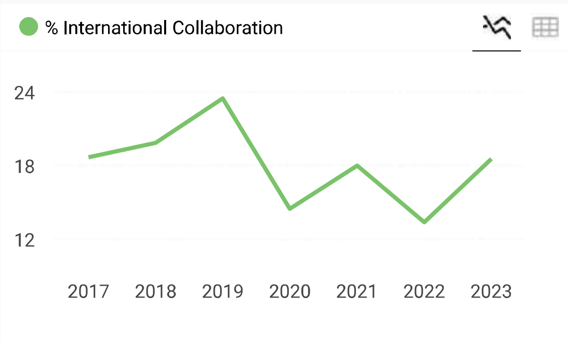
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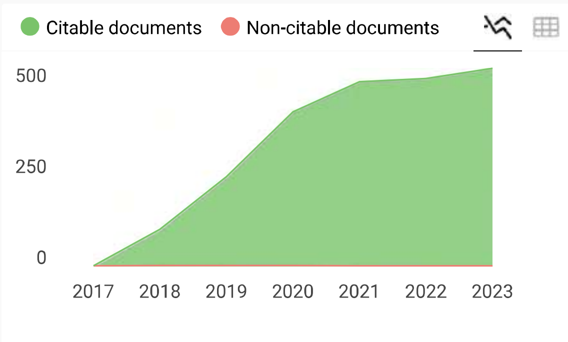
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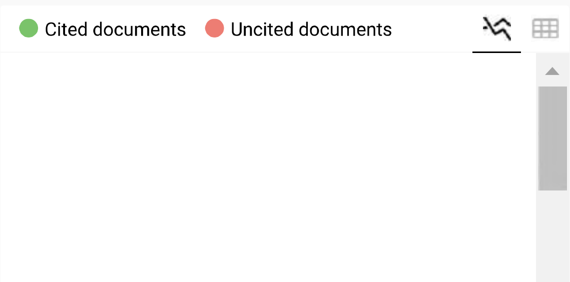
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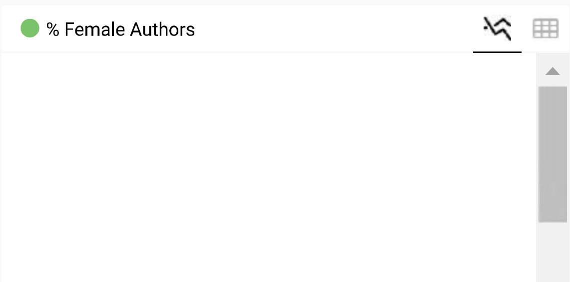
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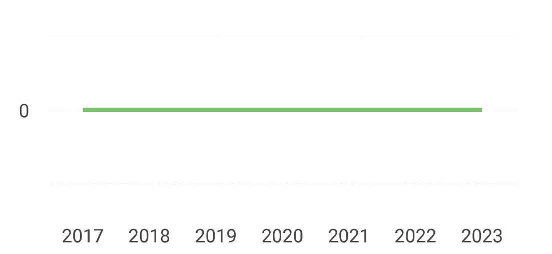

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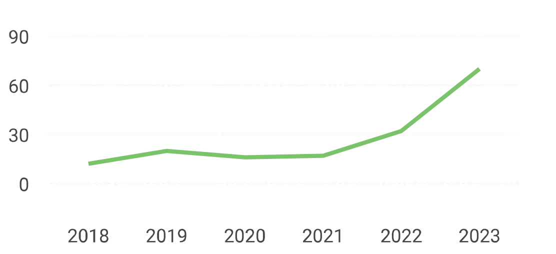

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