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Comparative Investigation of Half-mode SIW Cavity and Microstrip Hybrid Antenna Using Different Patch Shapes

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ABSTRACT

A set of hybrid microstrip patch and semi-circular cavity antennas is introduced. The semi-circular cavity is implemented using Half-mode Substrate Integrated Waveguide (HMSIW) technique. Different shapes of the patch including rectangular, semi-circular and equilateral triangular are excited using proximity effect by the semi-circular SIW cavity at its TM_{010} mode. The proposed antenna structures have been excited using an inset 50 Ω microstrip line that leads to a facility of planar circuit integration. The inherent limited bandwidth of the conventional microstrip patch antenna and SIW cavity-backed slot antenna is improved about 6% to 10% depending on the type of the patch using the proposed structure. Additionally, the proposed hybrid antenna enhanced the antenna gain by about 1.5 dB in comparison with the half-mode cavity without patch. Meanwhile, the proposed hybrid antennas made on a single-layer substrate has a low fabrication cost using printed circuit board (PCB) process. Three hybrid antennas are numerically and experimentally investigated. A comparative study between the three different structures contains gain, bandwidth, Cross Polarization Level (*CPL*) and Front to Back Ratio (*FBR*) is presented.

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1. INTRODUCTION

In recent years, microwave wireless communication systems have been rapidly developed and low profile, low cost and low loss circuits and antennas have been greatly needed. One way for compacting communication equipment is using planar structures. Printed patch and slot antennas have been widely investigated due to their attractive characteristics such as low-profile and compact size [1-3]. In spite of good features, these antennas suffer from their low bandwidth. Cavity backed antennas provide high performance radiation characteristics and eliminate backward radiation, and so provide higher gain [4-6]. The conventional metallic cavity backed antennas are bulky and their fabrication process is complicated. Also, they cannot easily integrate with planar circuits. Therefore, they are not suitable for many applications.

Recently, substrate integrated waveguide (SIW) technology has been suggested due to its usefull alternate to metallic waveguide. Therefore, implementation of microwave circuits and antennas is feasible using low cost Printed Circuit Board (PCB) process [7, 8]. Low-profile SIW cavity-backed slot antennas have been examined in [9, 10]. A size reduction of cavity-backed slot antenna using Half Mode SIW is investigated in [11]. A wideband cavity-backed slot antenna by using hybrid modes of cavity and employing a non resonat slot with a length more than a half resonant wavelength is presented in [12], and impedance bandwidth is increased from 1.5% to 6.3%. Also, using a wide slot in [13] and through a via-hole placed above the slot in [14], impedance bandwidth of cavity-backed slot antenna has been improved. SIW cavity-backed patch antennas are more considered due to their attractive characteristics such as reduction of cross polarization levels and elimination of surface waves [15]. A development of cavity-backed patch antenna array is presented in [16, 17], in which the

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antenna element has impedance bandwidth of 7% with 7.8 dBi gain. In [18], an E-shaped patch antenna backed by a SIW cavity has been investigated. Recently, a hybrid antenna including a rectangular patch and semi-circular SIW cavity antenna was introduced by authors [19]. Using proximity effect [20], a HMSIW cavity in conjunction with a patch, without any external matching circuit, a broadband antenna providing 9.5% fractional impedance bandwidth with 7.5 dBi gain is obtained, while antenna structure is made on a single layer substrate using a low cost PCB process.

In this paper, a set of hybrid antennas using a semi-circular SIW cavity in conjuction with different shaped patch including rectangular, semi-circlular and equilateral triangular are investigated numerically and experimentally. All the hybrid structures are wideband and provide high gain. A comparative study is investigated between these hybrid antenna structures including gain, bandwidth, Cross Polarization Level (*CPL*) and Front to Back Ratio (*FBR*).

2. ANTENNA DESIGN AND CONFIGURATION

Different proposed geometries of the hybrid patch and semi-circular SIW cavity antennas are shown in Figure 1. Different patches are simply located at the vicinity of the semi-circular cavity by distance *g*. All the antenna structures are implemented by means of a single substrate of dielectric constant ε_r and height *h*. Different shapes of the patch such as rectangular patch with length L_p and width W_p, semi-circular patch with radius R_p and equilateral triangular patch with length of a side a_p are printed on the top surface of the substrate layer, while an inset 50 Ω microstrip line with width *W* is printed on the backside of the substrate to excite the HMSIW cavity. The semi-circular cavity is realized by metallic via arrays, which have been placed in half of the circumference of a circle with radius R_c.

2. 1. Semi-circular SIW Cavity

Figure 2(a) shows simulated electric field distribution inside a circular SIW cavity coresponding to its TM_{010} mode. It can be seen that electric field lines are symmetric along *AB* plane. Consequently, the symmetrical plane can be considered as an equivalent quasi-magnetic wall. By dividing the circular cavity in to two halves along this plane, two semi-circular cavity is obtained and each half is called HMSIW resonator [21]. Field distribution of the semi-circular cavity is nearly same as the field distribution of half of the original circular cavity as shown in Figure 2(b). The semi-circular cavity due to its half mode configuration cannot support all modes of the original cavity. However, its frequency characteristics in supported modes are nearly same as the frequency properties of the original circular cavity. Therefore, the resonant frequency at TM_{010} mode of the semi-circular cavity can be calculated by Equation (1) [22]:

$$(f_{rc})_{010} = \frac{2.404c}{\pi R_c \sqrt{\mu_r \varepsilon_r}} \tag{1}$$

In which, R_c is the radius of the circular SIW cavity, μ_r and ε_r are relative permeability and permittivity of the filling material used for the SIW cavity. In addition, 2.404 denote the corresponding root of Bessel function and *c* stands for free space speed of light. In this case, simulated results show, circular and semi-circular cavities with a radius of R_c = 9.6 mm resonat at 8.1 GHz and 7.8 GHz, respectively, which shows that resonant frequencies of the two resonators have a little difference.

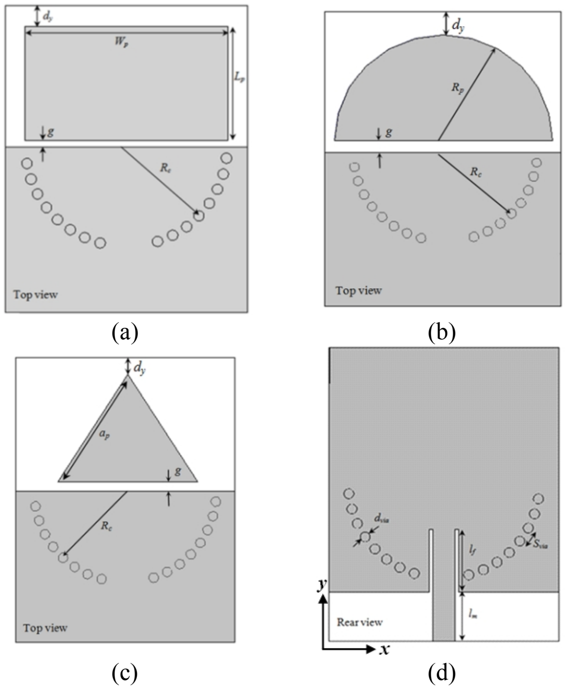


Figure 1. Geometry of the hybrid antennas with different patches: a) antenna I, b) antenna II, c) antenna III, d) rear view of all proposed antenna

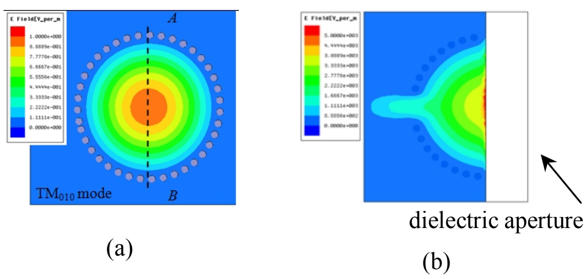


Figure 2. Electric field distribution of TM_{010} mode a) circular SIW cavity, b) half-mode SIW circular cavity

Electromagnetic waves are radiated through the dielectric aperture, whereas HMSIW circular cavity resonates at TM_{010} mode. Radiated fields far from the antenna are linearly polarized. The simulated results show that fractional impedance bandwidth of 1.5% with broadside radiation patterns is obtained. Meanwhile, antenna gain and radiation efficiency at resonant frequency are 5.6 dBi and 90%, respectively.

2. 2. Microstrip Patch Dimensions of the microstrip patches can be determined by considering their resonant frequency and its operating mode. For the rectangular microstrip patch, dimensions can be evaluated by Equations (2) and (3) [1]:

$$W_p = \frac{c}{2\, f_{rp}} \sqrt{\frac{2}{\varepsilon_r + 1}} \tag{2}$$

$$L_p = \frac{c}{2\, f_{rp} \sqrt{\varepsilon_{re}}} - 2\Delta L \tag{3}$$

where, f_{rp} is resonant frequency of TM_{010} mode of the rectangular patch, ε_{re} is the effective permittivity and ΔL is extended incremental length of the patch.

The semi-circular patch is the same as a circular patch if a magnetic wall inserted along the diagonal of circular patch [23]. So, the dominant mode of the semi-circular patch is TM_{110} mode of the circular patch and patch radius can be evaluated by Equation (4) [23]:

$$R_p = \frac{3.0542\, c}{2\pi\ f_{rp} \sqrt{\varepsilon_r \mu_r}} \tag{4}$$

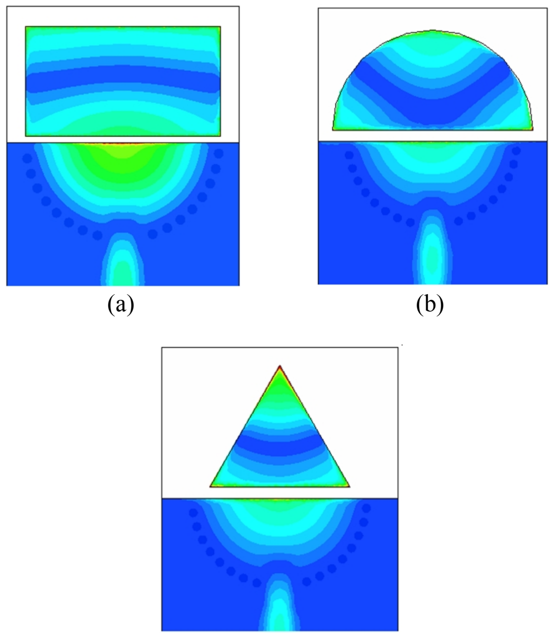
where, 3.0542 represents the corresponding root of derivative Bessel function.

Using cavity model, the triangle patch is enclosed by a magnetic wall along the periphery. The length of a side for an equilateral triangular patch for the dominant mode TM_{010} can be estimated by Equation (5) [23]:

$$a_p = \frac{2\, c}{3\, f_{rp} \sqrt{\varepsilon_r \mu_r}} \tag{5}$$

In all three antennas, fields of the semi-circle SIW cavity are coupled with fields of patches throught the dielectric aperture. The amount of coupling between the cavity and patch depends on the existing mode of the cavity, patch shapes and also the distance between the two resonators. Electric field of the SIW cavity at TM_{010} mode is in compatible with electric field of the rectangular patch, semi-circular patch and equilateral triangular patch corresponding to their TM_{010}, TM_{110} and TM_{010} modes, respectively. Consequently, the dominant mode of the patches is excited by the dielectric aperture fields. Figure 3 shows electric field distribution of all proposed structures. It can be observed that electric field distribution of the cavity and patches are well coupled together. In each structure, there exist two resonators, one of them is the semi-circular cavity and the other one is the microstrip patch. By proper choice of resonator dimensions, resonant frequency of the cavity and the microstrip patch could be merged and in turn, wide bandwidth is achieved. The initial approximation of the geometrical dimensions of the resonators could be independently estimated by Equations (1) to (5). However, a parametric study is carried out using HFSS software to obtain optimized parameters for wide impedance bandwidth.

2. 3. Substrate Properties Generally, impedance bandwidth of the antenna is inversely proportional to $\sqrt{\varepsilon_r}$ [1], in which ε_r is relative permitivity of the substrate. In the proposed antenna structures, the SIW cavity and patch are implemented using a single layer substrate. Thickness and dielectric constant of the substrate are highly affected on the bandwidth of cavity backed antenna. In addition, in microstrip antennas, to minimize both dielectric and surface wave losses, low-loss material is preferred [1]. Therefore, for the two resonators, semi-circular cavity and patch, a thin and low ε_r substrate is recommended. Finally, the vias diameters and distance between them are properly selected in order to make the semi-circular SIW cavity acts similarly to a conventional metallic cavity [7].



(a) (b)

(c)

Figure 3. Electric field distribution of the proposed hybrid antennas : a) antenna I, b) antenna II, c) antenna III

TABLE 1. Geometrical parameters of the proposed antennas (units in: mm)

parameters	Antenna I	Antenna II	Antenna III
l_f	6.4	5.5	6.4
g	0.65	1.3	1.3
d_y	2	3	2
R_c	9.6	9.6	9.6
l_m	5	5	5
d_{via}	1	1	1
S_{via}	1.5	1.5	1.5
L_p	11.08	-	-
W_p	19.5	-	-
R_p	-	11.5	-
a_p	-	-	15.5

3. RESULTS AND DISCUSSION

3. 1. Simulation Results The proposed hybrid antennas are designed to operate at 8 GHz. TLY031 high-frequency laminate with electrical characteristics including ε_r of 2.2, tangent loss of 0.001, and thickness of h=0.787 mm corresponding to $0.02\lambda_0$ is selected for substrate. Geometrical designed parameters of all antennas are summarized in Table 1. All three antennas are numerically investigated using HFSS software, while conductor and dielectric losses are taken into account in simulation process.

Figure 4 shows the simulated results of reflection coefficient for three antennas. It can be seen that all three antennas provide two separate resonant frequency, which confirms that resonant frequencies of both resonators are merged and broadband impedane is achieved. Antenna I, using rectangular patch, shows 780 MHz bandwidth for reflection coefficient below -10 dB, while, antennas II and III show impedance bandwidth of 563 MHz and 476 MHz, respectively. This means that three different hybrid antennas show fractional impedance bandwidth of nearly 9.6%, 7.1% and 6% for rectangular, semi-circular and triangular patches, respectively. Moreover, antenna I offer wider impedance bandwidth compared to the bandwith of the other antennas. This may be due to the better coupling and lower Q of the rectangular patch at its dominant mode than that of the other patches. However, different shapes of the patch in proposed hybrid antennas provides wider bandwidth compared to typically impedance bandwidth of 1.5% of the conventional microstrip patch antenna. The simulated gain and radiation efficiency versus frequency of the different patches are shown in Figure 5. It can be seen that antennas gain is nearly flat over the frequency bandwidth and exhibit a peak gain of 7.6 dBi, 7.35 dBi and 7.1 dBi for antennas I, II and III, respectively. Simulated radiation efficiency for all antennas is at least 90% in their operating bandwidth. These results indicate that the proposed hybrid antennas have high radiation efficiency and antenna gain has been enhanced more than 1.5 dB compared to the gain of HMSIW circular cavity antenna without patch.

The simulated radiation patterns of the proposed antennas in two principle cut planes; H- (φ=0°) and E-plane (φ=90°), including co- and cross-polarization patterns are illustrated in Figures 6(a) and 6(b), respectively. These results show that the proposed antennas have similar co-polarization patterns in H-plane. Also, their E-plane patterns are nearly the same. In terms of the *CPL*, the antenna with semi-circular patch has higher cross-polarization in H-plane. The simulated results in Figure 6 show that half power beam width (HPBW) in H- plane are nearly from 72° to 78° and in E-plane are approximately from 72° to 82° for the three antennas. The simulated front-to-back ratio (FBR) within the HPBW is -21.93 dB, -21.79 dB and -19.46 dB for the antennas I, II and III, respectively. The simulated characteristics of the three hybrid antennas are summarized in Table 2.

3. 2. Experimental Results Considering the best radiation performance of the three proposed hybrid antennas, antenna I using rectangular patch is fabricated and exprimentaly investigated. Photo of the fabricated antanna is illustrated in Figure 7. Measured results of reflection coefficient, gain and radiation patterns including simulation ones are shown in Figure 8(a) and 8(b). Also, measured and simulated radiation characteristics of this antenna is listed in Table 3. A very good agreement can be seen between the simulated and measured results. In comparison with the applied methods for increasing bandwidth of a microstrip antenna, the proposed hybrid structure in this paper improve both impedance bandwidth and gain of the antenna. The proposed hybrid antenna enhanced impedance bandwidth nearly 7.5% and antenna gain by 2 dB compared to the HMSIW cavity bandwidth and gain without patch. It is noted that proposed antenna has wider impedance bandwidth and higher gain compared to the bandwidth and gain of a conventional microstrip patch antenna.

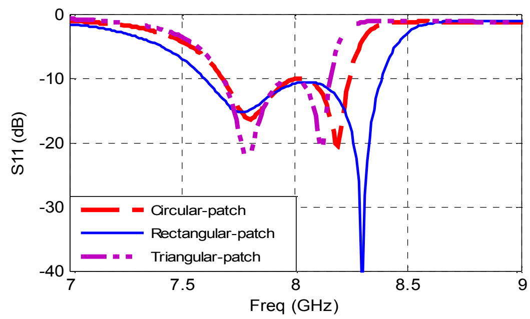


Figure 4. Simulated reflection coeffient of the different proposed hybrid antennas

TABLE 2. Summary of the simulated radiation characterestics of the proposed antennas

	Antenna I	Antenna II	Antenna III
Bandwidth (%)	9.6	7.1	6
Gain (dB)	7.6	7.35	7.1
FBR (dB)	21.47	21.79	19.45
HPBW in H-plane	72˚	72˚	78˚
HPBW in E-plane	76˚	72˚	82˚
H-plane *CPL* (dB)	-27.8	-15.25	-29.5
E-plane *CPL* (dB)	-36.3	-32.2	-33.8

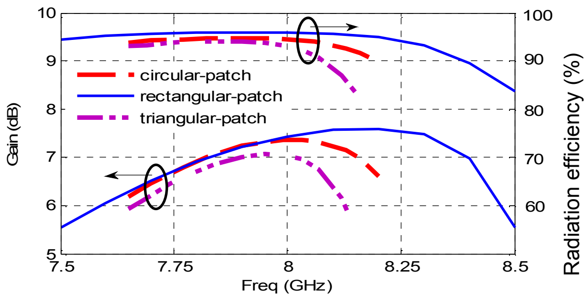
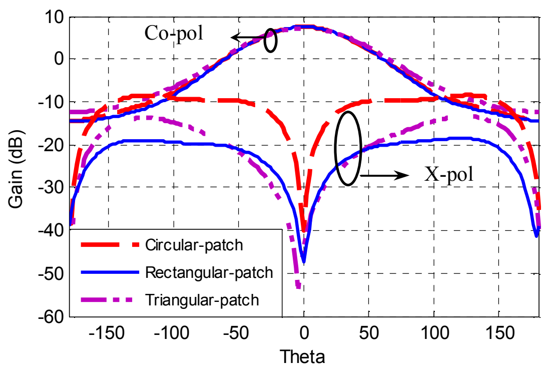
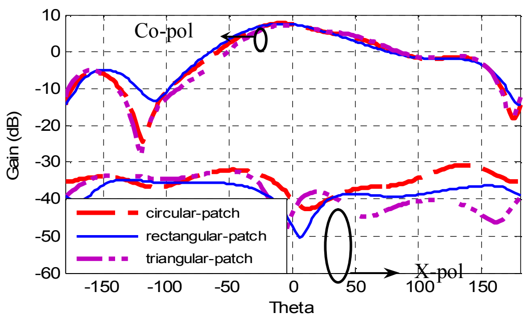


Figure 5. Simulated gain and radiation efficiency of the different proposed hybrid antennas



(a)



(b)

Figure 6. Simulated radiation patterns of the different hybrid antennas including co- and cross-polarization patterns at 8 GHz : a) H-plane, b) E-plane.

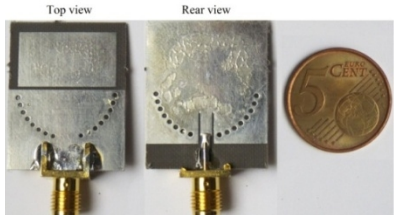
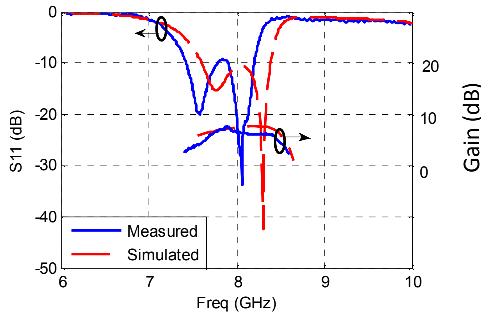
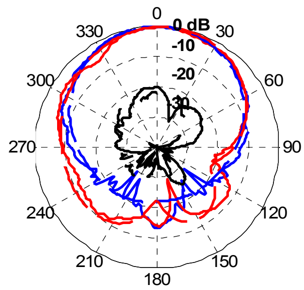


Figure 7. Photo of the fabricated Antenna I



(a)



(b)

	Co-Pol (Measured)	X-Pol (Measured)	Co-Pol (Simulated)
E-plane			
H-plane			

Figure 8. Simulated and measured results of Antenna I: a) reflection coefficient and gain, b) radiation patterns at 8 GHz

TABLE 3. Summary of the measured and simulated radiation characterestics of the hybrid antenna I

	measured	simulation
Bandwidth (%)	10	9.6
Gain (dB)	7.5	7.6
***FBR* (dB)**	13.2	21.47
HPBW in H-plane	82˚	72˚
HPBW in E-plane	71˚	76˚
H-plane *CPL* (dB)	-21	-27.8
E-plane *CPL* (dB)	-22	-36.3

Howevere, thiner substrate thickness about 0.02 λ_0 and enclosed structure of the cavity reduc surface wave and retain advantages of the cavity-backed antenna such as high gain, high radiation efficiency and low backward radiation.

4. CONCLUSION

In this paper, a set of new hybrid antennas including a semi-circular SIW cavity and microstrip patch providing wide impedance bandwidth is proposed. Different shaped patch including rectangular, semi-circlular and equilateral triangular are investigated numerically and experimentally. All proposed hybrid antennas are excited by an inset 50 Ω microstrip line, which facilitate integration with planar circuits and directly connection to a SMA connector. Also, they are implemented only on a single substrate using low cost PCB process. It is shown that placing a mircrostrip patch at an appropriate distance along the dielectric aperture of an HMSIW cavity-backed antenna, enhances antenna bandwidth and gain effectively. These hybrid antennas have been numerically investigated and results indicated fractional impedance bandwidth wider than 6% and gain higher than 7 dB. The best type of the proposed hybrid antennas, rectangular patch hybrid antenna which providing maximum impedance bandwidth is fabricated. The measured fractional impednace bandwidth of 10% with 7.5 dBi gain for is also obtained.

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چکیده

در این مقاله یک مجموعه از آنتن‌های ترکیبی شامل محفظه نیم دایره‌ای با فناوری موجبر مجتمع شده در زیر لایه و پچ مایکرواستریپ معرفی شده است. محفظه نیم دایره‌ای توسط فناوری موجبر مجتمع شده در زیر لایه نیم مود (HMSIW) پیاده-سازی شده است. شکل‌های مختلف از پچ شامل مستطیلی، نیم دایره‌ای و مثلثی متساوی الاضلاع با استفاده از اثر مجاورت توسط حفره SIW دایروی در مود کاری TM_{010}، تحریک شده‌اند. ساختارها توسط خط مایکرواستریپ تحریک شده و این امر مجتمع شدن ساختار با مدارهای مسطح را تسهیل می‌کند. محدودیت ذاتی پهنای باند آنتن‌های پچ مایکرواستریپ و شکاف‌های تحت حمایت حفره SIW، حدود ٦ ٪ تا ١٠٪ بسته به نوع پچ به‌کار رفته، بهبود می‌یابد. همچنین آنتن ترکیبی پیشنهادی حدود dB ۱/۵ بهره را افزایش داده، در حالی‌که آنتن ترکیبی پیشنهادی با هزینه ساخت کم توسط فرآیند مدار چاپی بر روی یک زیر لایه ساخته شده است. سه آنتن ترکیبی به صورت عددی و تجربی بررسی شده و مقایسه‌ای بین مشخصات این ساختارها از نظر بهره، پهنای باند، سطح قطبش مخالف و مقدار *FBR* نیز ارائه شده است.

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