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Design and Simulation 4×4 Butler Matrix Array for ISM-Band

Ayman N. Salman Younis
Department of Electrical Engineering, College of Engineering, University of Thi-Qar, Nasiriyah, Iraq

Abstract: This study proposes an 4×4 planar microstrip array antenna with Butler matrix performing network can be used for a switched beam smart antenna system. The prototype antenna is operating in the ISM from 2.4-2.48 GHz for WLAN applications. The antenna is built on a FR4 substrate with relative permittivity of ε_r = 4.4, loss tangent of 0.02 and thickness of h = 1.6 mm. The performance of this smart antenna system was optimized and simulated by using commercially available full-wave, Method of Moment (MOM) based electromagnetic simulator Zeland IE3D.

Key words: Switch beam smart antenna system, Butler matrix, microstrip, electromagnatic, substrate, tangent

INTRODUCTION

Mitigation of interference and multipath due to multiple signals coexisting in the same frequency band can be achieved through the implementation of a smart antenna system (El-Zooghby, 2005; Winters, 1998; Godara, 2004) that can focus their radiation pattern toward the desired direction and rejecting unwanted interferences. These systems can generally be classified as either switched-beam or adaptive array. Switched beam systems have several available fixed beam patterns. A decision is made as to which beam to access at any given point in time based upon the requirements of the system. One of the most important switch beam system can be generated through beamforming networks such as the Butler matrix (Neron and Delisle, 2005; Wu, 2007). It is N×N passive feeding network with N radiating elements. One characteristic of Butler matrices is that the overall circuit grows exponentially as N increases. Although increased N will mean more multiple beams, this advantage comes with it, the expense of increased circuit size. Microstrip antennas (Sainati, 1996; Kumar and Ray, 2003) offer the advantages of thin profile, light weight, low cost, ease of fabrication and compatibility with integrated circuitry. In this study, researchers are using microstrip antenna technique to implement the Butler matrix array to achieve suitable size and performance for ISM-band applications.

The proposed 4×4 Butler matrix is such a network as shown in Fig. 1 which can be realized with 4 hybrid couplers, 2 phase shifters and 2 crossovers. This study details also presents mathematical calculations the optimum design and simulation results of Butler matrix and all its individual components.

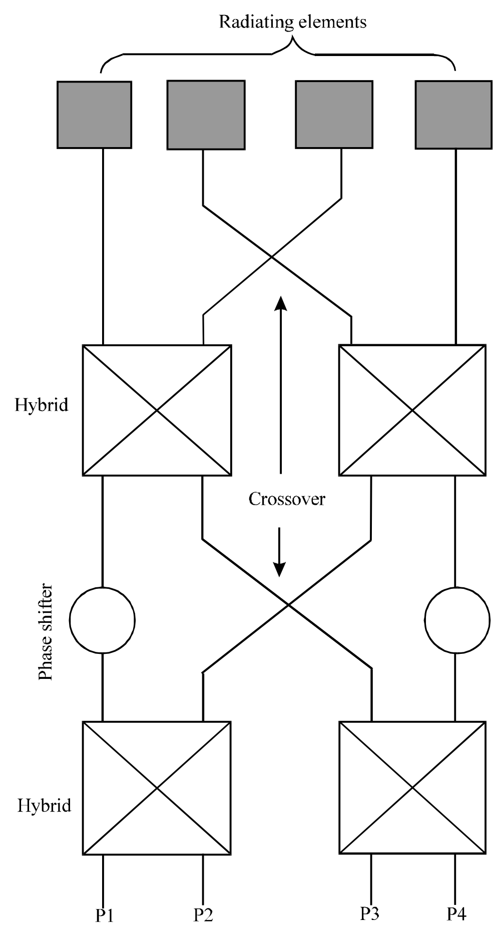

Fig. 1: Layout of the 4×4 Butler matrix

BEAMFORMING NETWORK CONFIGURATION

The Butler matrix is used as a beamforming network that allows to produce orthogonal beams that can be steered in different directions. It is a N×N network consisting of N inputs, N outputs, N log, N hybrids and some phase shifters to form the beam pattern (Denidni and Libar, 2003). From Fig. 1, it has 4 inputs P1-P4 and 4 outputs 5-8 are used as inputs for antenna elements to produce 4 beams. Some mathematical equations used to calculate the width and the length of the transmission lines. For a given characteristic impedance Z_0 and dielectric constant ε_r, the W/h ratio can be found as (Pozar, 2005):

$$\frac{W}{h}=\begin{cases}\dfrac{8e^{A}}{e^{2A}-2} & \text{for } \dfrac{W}{h}<2\\ \dfrac{2}{\pi}\left[B-1-\ln(2B-1)+\dfrac{\varepsilon_r-1}{2\varepsilon_r}\times\left\{\ln(B-1)+0.39-0.\dfrac{61}{\varepsilon_r}\right\}\right] & \text{for } \dfrac{W}{h}>2\end{cases} \quad (1)$$

$$A=Z_0\sqrt{\frac{\varepsilon_r+1}{2}}+\frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23+\frac{0.11}{\varepsilon_r}\right)$$

$$B=\frac{377\pi}{2Z_0\sqrt{\varepsilon_r}}$$

THE HYBIRD COUPLER

Quadrature hybrid is 3 dB directional coupler with 90° out of phase at its output. It consists as shown in Fig. 2 of a main line which is coupled to a secondary line by two quarter-wavelength long sections spaced one quarter wavelength apart. The basic of properties of the quadrature hybrid can be deduced directly from the scattering matrix which is given by (Pozar, 2005):

$$[S]=\frac{-1}{\sqrt{2}}\begin{bmatrix}0 & j & 1 & 0\\ j & 0 & 0 & 1\\ 1 & 0 & 0 & j\\ 0 & 1 & j & 0\end{bmatrix} \quad (2)$$

Typically, the input is at port 1 and the output ports 2 and 3 while the isolated port 4 is terminated in a match load. In this study, 90° hybrid is designed by two (Z_0 = 50 Ω) and two (Z_0 = 35.4 Ω) transmission lines with length L can be calculated as:

$$L=\frac{c}{4f_r\sqrt{\varepsilon_{reff}}} \quad (3)$$

where, f_r is the design frequency and ε_{reff} denotes the effective dielectric constant given by (Pozar, 2005):

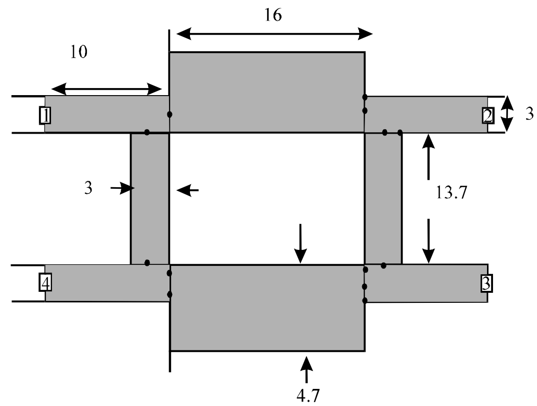

Fig. 2: The optimized quadrature hybrid (dimensions in mm)

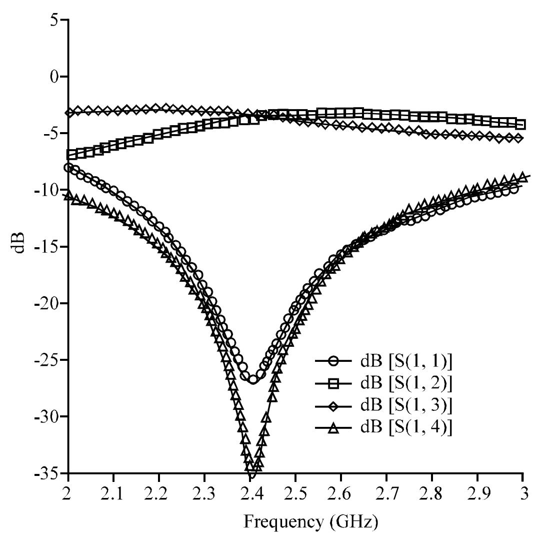

Fig. 3: S parameters magnitudes versus frequency for the 3 dB quadrature hybrid

$$\varepsilon_{reff}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12\,h/W}} \quad (4)$$

Optimization design of 90° hybrid obtained by Zeland IE3D is given with the dimensions in Fig. 2. The simulated magnitudes for the quadrature hybrid S11-S14 magnitudes for the quadrature hybrid are −27, −3.5, −3.5 and −34.5 dB, respectively as shown in Fig. 3. As expected, the phase difference between port 3 and port 2 is 90°.

THE CROSSOVER COUPLER

The crossover can be build simply by cascading two 90° hybrids (Pozar, 2005). It is also a symmetrical four port network with 2 inputs and 2 outputs. The perfect design of crossover is accomplished if every adjacent ports are isolated such that if port 1 is fed, the output of ports 2 and 4 should be equal to 0 and if port 4 is fed, the output of ports 1 and 3 should be 0. The (S) matrix will have the following form (Pozar, 2005):

$$[S] = \begin{bmatrix} 0 & 0 & j & 0 \\ 0 & 0 & 0 & j \\ j & 0 & 0 & 0 \\ 0 & j & 0 & 0 \end{bmatrix} \quad (5)$$

In the same way, the crossover has been optimized with the dimensions in Fig. 4. It has 50 Ω microstrip line and the results are shown in Fig. 5. The insertion loss for the coupled port S13 is -0.8 dB while return loss S11 is -21dB and the isolated ports S12 and S14 are -18 and -32 dB, respectively for the frequency band of interest.

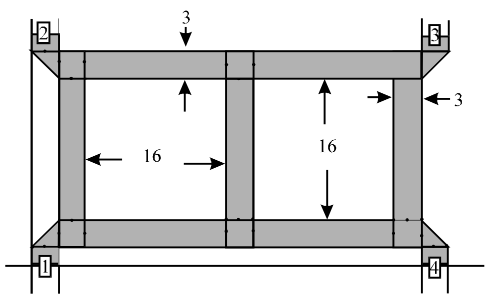

Fig. 4: The optimized crossover coupler (dimensions in mm)

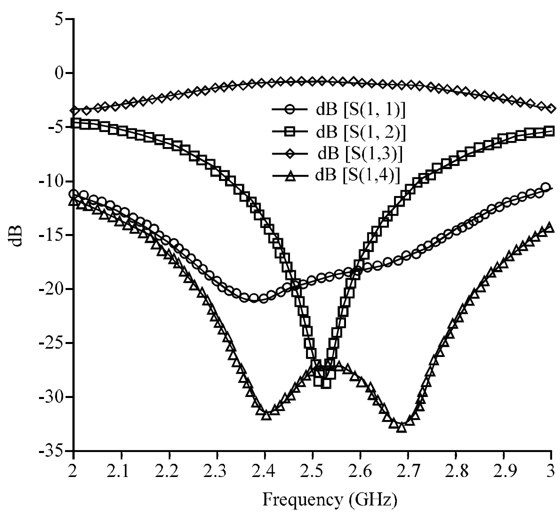

Fig. 5: S parameters magnitudes versus frequency for the crossover coupler

PHASE SHIFER

Every line that is longer than a reference line by a certain amount introduces phase shift. The length l_p of a line required to generate a phase shift of θ° can be found as:

$$l_p = \frac{|\theta|}{2\pi}\lambda_g \quad (6)$$

Where $\lambda_g = \lambda/\sqrt{\varepsilon_{reff}}$ denotes the guided wavelength. The optimum design for 50 Ω microstrip line with -45° phase shift was achieved with the dimensions as shown in Fig. 6 and 7.

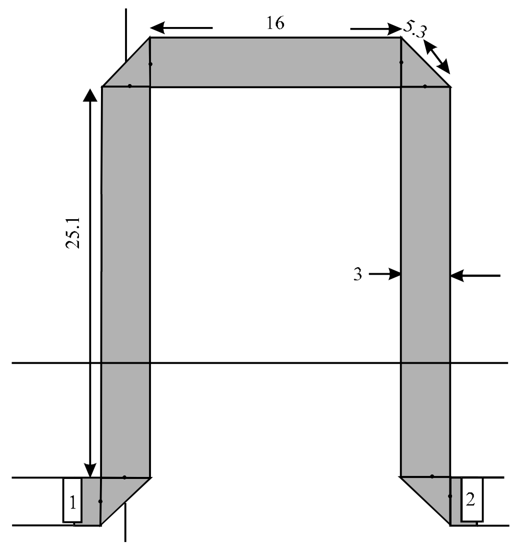

Fig. 6: The optimized -45° phase shifter (dimensions in mm)

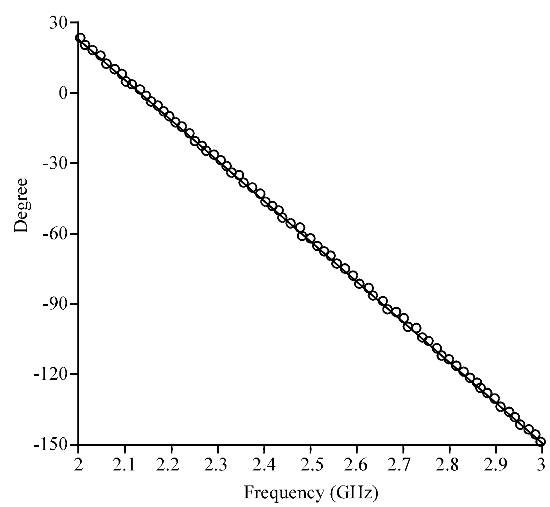

Fig. 7: Phase shiftining = -45°; Ang [S(2, 1)]

MICREOSRIP PACH ANTENNA

The rectangular patch is by far the most widely used in Butler matrix configuration. The 1st step of the design procedure of a rectangular patch antenna is to compute its physical dimensions. For an efficient radiator, a practical width that leads to good radiation efficiencies is (Balanis, 2005):

$$W = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \quad (7)$$

where, v_0 is the free-space velocity of light. The practical approximation of the normalized extension of length is (Balanis, 2005):

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \quad (8)$$

The actual length of the patch can be determined as (Balanis, 2005):

$$L = \frac{v_0}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L \quad (9)$$

The position of the inset feed point where the input impedance R_m is 50 Ω can be calculated as (Balanis, 2005):

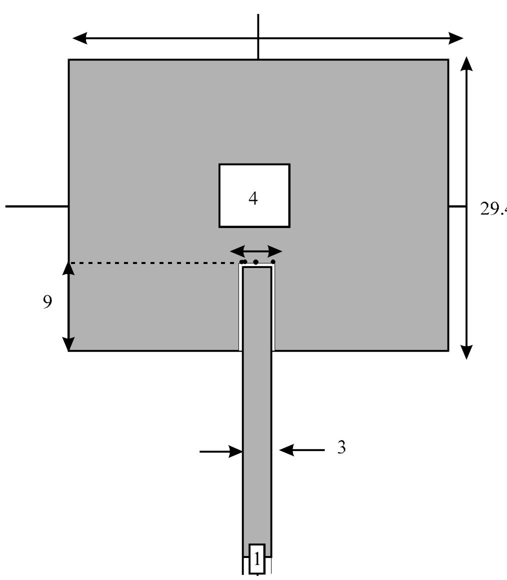

Fig. 8: The optimized design of one radiated element microstrip patch antenna

$$R_m(y = y_0) = R_m(y = 0)\cos^2\left(\frac{\pi}{L}y_0\right) \quad (10)$$

Where y_0 is the position of the feed from the edge along the direction of the length L of the patch. The optimum design with the dimensions is shown in Fig. 8. The optimum feed point is found to be at 9 mm offset from the edge where a Return Losses (RL) of −26 dB is shown in Fig 9. Figure 10 shows the gain of the antenna at 2.4 GHz for f = 0 and 90°.

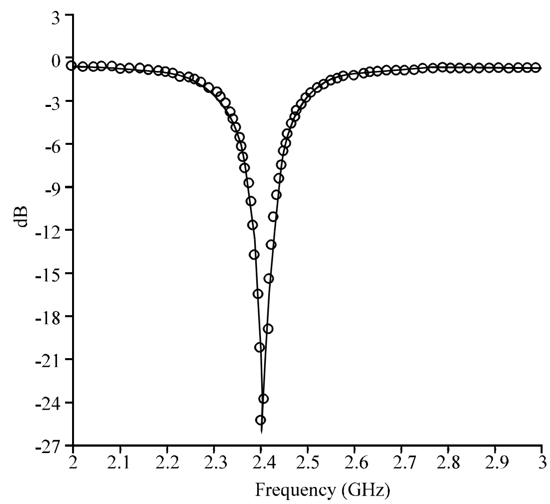

Fig. 9: Return loss for one radiated element microstrip patch antenna; dB [S(1,1)]

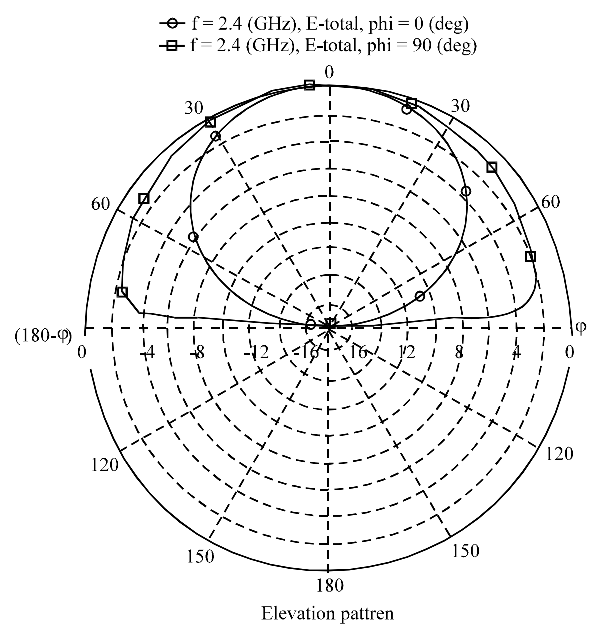

Fig. 10: Elevation patern gain display (dB)

OPTIMUM DESIGNOF 4×4 BUTLER MATRIX

The final layout of the optimized Butler matrix array is shown in Fig. 11. Figure 12a-h show the isolations, return losses and couplings of the Butler matrix in the operation frequency band of about 2.4-2.48 GHz. It can be seen that the isolations from fours input ports are greater than -18 dB. The couplings show almost constant magnitude at the output ports. The radiation pattern of the arrays are shown in Fig. 13.

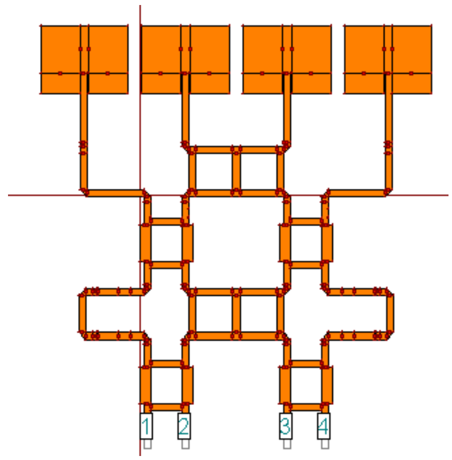

Fig. 11: Final layout of 4×4 butler matrix array antenna

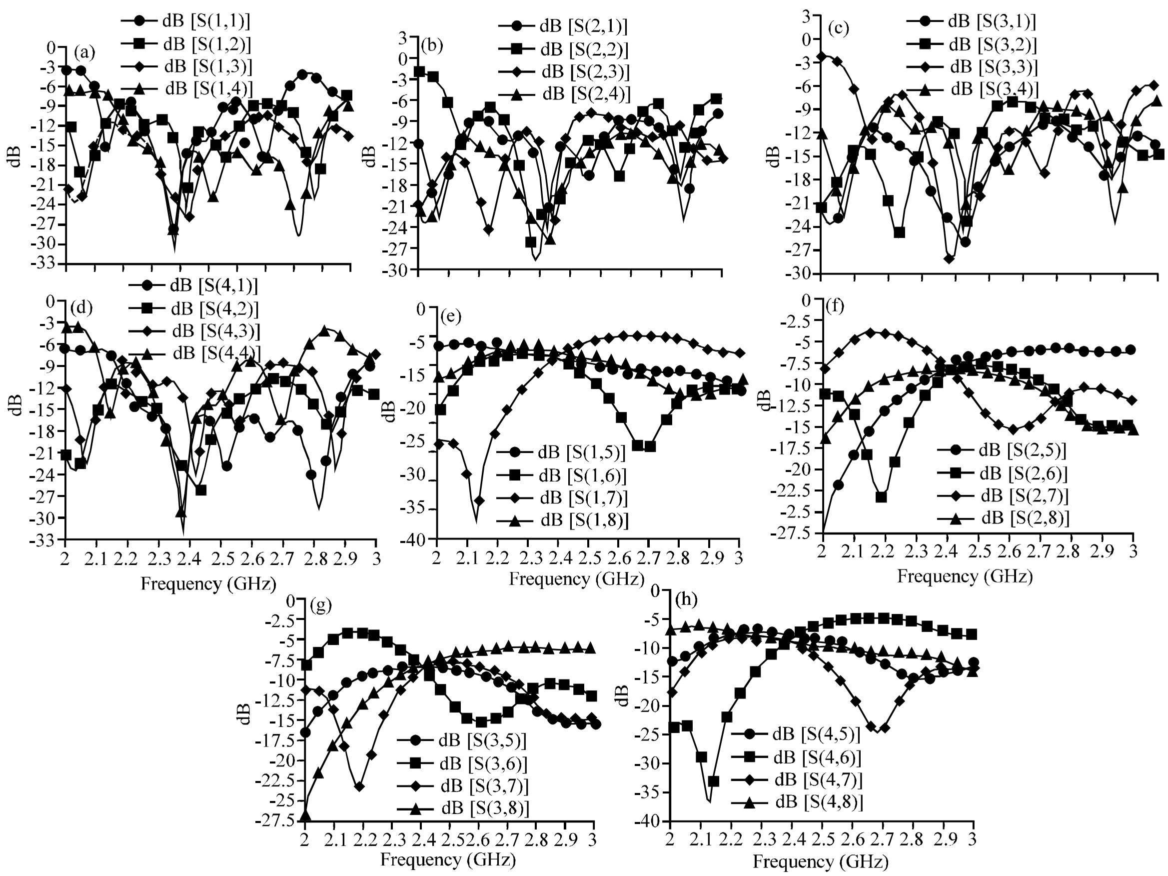

Fig. 12: a-h) The isolations, return losses and couplings of the 4×4 butler matrix in the operation frequency band of about 2.4-2.48 GHz

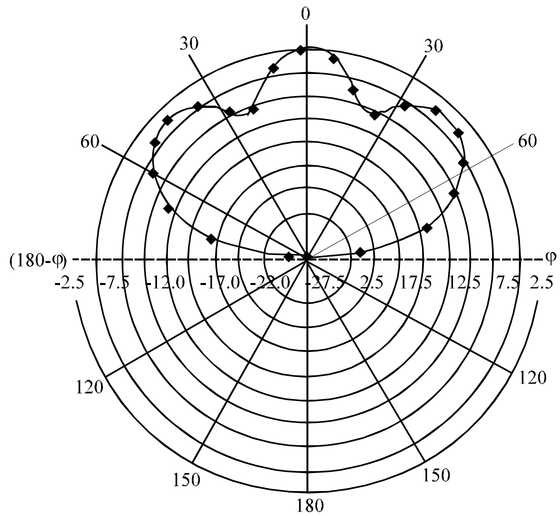

Fig. 13: Radiation pattern of 4×4 butler matrix array when all ports are fed at 2.4 GHz; f = 2.4 GHz, E-total, phi = 0°

It clearly depicts that the 4-beam smart antenna generates four orthogonal beams to cover 120° area.

CONCLUSION

The 4×4 butler matrix has been design to cover 120° cellular area. All components of the Butler matrix (microstrip antenna, hybrid couplers, cross-coupler, phase shifter) are also given with dimensions to operate over ISM-band from 2.4-2.48 GHz of WLN applications. Then all the components are designed and simulated using commercial software Zeland IE3D. Reasonable isolations, return losses and couplings are obtained.

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