Progress In Electromagnetics Research Letters, Vol. 42, 167–176, 2013

INVESTIGATION OF WIDEBAND ONE-STEP STAIR-SHAPED DIELECTRIC RESONATOR ANTENNAS

Meng Zou*, Jin Pan, Le Zuo, and Zai-Ping Nie

Department of Microwave Engineering, School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu 611731, P. R. China

Abstract—The one-step stair-shaped dielectric resonator antennas (DRAs) with a circular cross-section are studied theoretically and experimentally in this paper. The reasons why the one-step stair-shaped DRAs have a wideband performance have been investigated. It is shown in this paper that the modes excited in the one-step stair-shaped DRA with circular cross-section can be regarded as pseudo HEM_{111} and pseudo HEM_{113} modes. The pseudo HEM_{111}/HEM_{113} mode exhibits similar radiation patterns but a different resonant frequency and radiation Q factor to the HEM_{111}/HEM_{113} mode of the cylindrical DRA. By properly choosing the dimensions of the one-step stair-shaped DRA, the two modes can be used to obtain a wideband antenna.

1. INTRODUCTION

There has been increasing interest in investigations of the dielectric resonator antennas (DRAs) [1–4]. DRAs are known for the inherent merits of small size, ease of excitation, low dissipation loss and high radiation efficiency [5]. However, the typical bandwidth of the regular-shaped DRAs is about 10%.

In recent years, various methods have been investigated to broaden the bandwidth of the DRAs [6–18]. Using a stair-shaped DRA is one of the ways to achieve a wide impedance bandwidth ($S_{11} < -10\,\mathrm{dB}$) [9–12]. Bandwidths of 32% and 44% are obtained with a slot-coupled one-step stair-shaped DRA [12] and a probe-fed one-step stair-shaped DRA [9], respectively, and when another step is added a wider bandwidth of 62% is achieved for the two-step stair-shaped DRA [10].

Received 29 July 2013, Accepted 2 September 2013, Scheduled 5 September 2013
* Corresponding author: Meng Zou (zm.1598@163.com).

However, the reason why the stair-shaped DRA has a wideband performance has not been made clear. This means that the modes excited in the stair-shaped DRA are not clearly identified. So it might be different to design such an antenna at other frequencies.

Another bandwidth enhancement technique is based on merging the frequency bands of the dual-band antennas [13–18]. Dual-mode DRAs are one kind of these types of antenna [14–18]. In [18] a bandwidth of 23.5% is obtained by making use of the HEM_{111} and HEM_{113} modes of a cylindrical DRA.

In this paper, the properties of the resonant modes in the one-step stair-shaped dielectric resonator (DR) are investigated. The investigation explains why the one-step stair-shaped DRA has a wide impedance bandwidth, and it can serve as the basis for further study of the more complex two-step stair-shaped DRA. The one-step stair-shaped DRA with a circular cross-section (shown in Fig. 1) can be considered as a variation of the cylindrical DRA. And the cylindrical DRA is a special case of the stair-shaped DRA with a circular cross-section. It is found in this paper that the lowest two broadside modes of the one-step stair-shaped DRA with a circular cross-section can be regarded as pseudo HEM_{111} and pseudo HEM_{113} modes. The radiation pattern of pseudo HEM_{111}/HEM_{113} mode is similar to the HEM_{111}/HEM_{113} mode. And the resonant frequencies and radiation Q factors of the pseudo HEM_{111} and pseudo HEM_{113} modes will decrease with an the increase in of the cross-section size of the top layer. However, it is found that the pseudo HEM_{113} mode is more sensitive to the top layer than the pseudo HEM_{111} mode. So the frequency bands of the two pseudo modes can be merged by increasing the cross-section size of the top layer, and then a wide bandwidth can be obtained.

The organization of the paper is as follows. The lowest two broadside modes (pseudo HEM_{111} and pseudo HEM_{113} modes) of the one-step stair-shaped dielectric resonator (DR) are studied and the reason why the one-step stair-shaped DRA has a wideband is explained in Section 2. A prototype of wideband slot coupled one-step stair-shaped DRA has been designed to validate the proposed concept in Section 3. Finally, Section 4 concludes the results of the investigations and considers the prospect of future research developing out of the study presented here.

2. RESONANT MODES OF THE ONE-STEP STAIR-SHAPED DR

The geometry of the one-step stair-shaped DR placed above a ground plane is shown in Fig. 1. The DR has a relative permittivity of $\varepsilon_r = 12$.

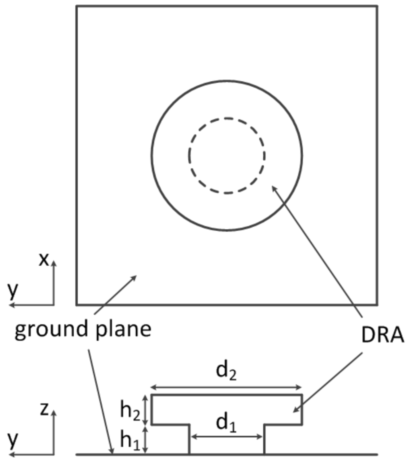

Figure 1. Geometry of the one-step stair-shaped DR placed on a ground plane.

The DR is in a one-step flipped stair form with circular cross-section. The base has a diameter of d_1 and a height of h_1 while the top layer has a diameter of d_2 and a height of h_2.

It is obvious that the one-step stair-shaped DR becomes a cylindrical DR when $d_1 = d_2$. And as we know, the fundamental broadside mode of the cylindrical DRA is HEM_{111} mode [5]. To study that of the one-step stair-shaped DRA, Ansoft HFSS is employed to analyze the modes in the one-step stair-shaped DR. The whole model of the DR is enclosed by a big closed cavity with a perfect matched layer (PML) boundary, and the solution type of eigen mode is used to analyze the frequency and Q factor of resonant modes of the DR. Two one-step stair-shaped DRs are simulated: the dimensions of the first one are $d_1 = d_2 = 25\,\text{mm}$ and $h_1 = h_2 = 10\,\text{mm}$, those of the second one are $d_1 = 25\,\text{mm}$, $d_2 = 50\,\text{mm}$, and $h_1 = h_2 = 10\,\text{mm}$. The H-fields of the fundamental broadside mode in the first DR are shown in Fig. 2, and those of the second one are shown in Fig. 3 (the DRs are mounted on the ground plane). The resonant frequencies and Q factors of the fundamental broadside modes in the two DRs are shown in Table 1.

Table 1. The resonant frequencies and Q factors of the fundamental broadside modes in the two DRs.

d_2	resonant frequency	Q factor
25 mm	2.53 GHz	17.32
50 mm	2.40 GHz	14.18

As shown in Fig. 2 and Fig. 3, the field distributions in the two DRs are similar, both like a short magnetic dipole. Therefore, the fundamental broadside mode of the one-step stair-shaped DRA can be called pseudo HEM_{111} mode. Table 1 shows that when d_2 changes from 25 mm to 50 mm, the resonant frequency and the Q factor of the one-step stair-shaped DR only decrease by 5% and 18%, respectively. This is because the fields of the modes are concentrated at the bottom of the DRs. So the top layer of the one-step stair-shaped DR plays a minor role in the properties of the pseudo HEM_{111} mode. According to the relationship between the bandwidth and the Q factor of the DRA [5], the tiny decrease of the Q factor is not the only reason why

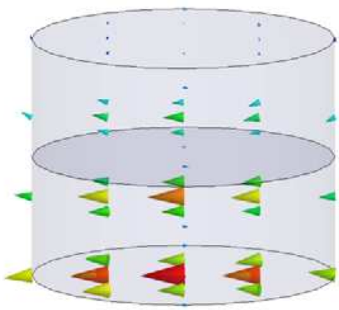

Figure 2. H-field of the fundamental broadside mode in the first DR (the DR is mounted on the ground plane).

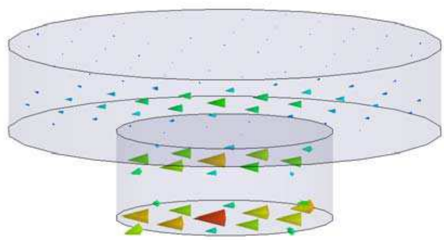

Figure 3. H-field of the fundamental broadside mode in the second DR (the DR is mounted on the ground plane).

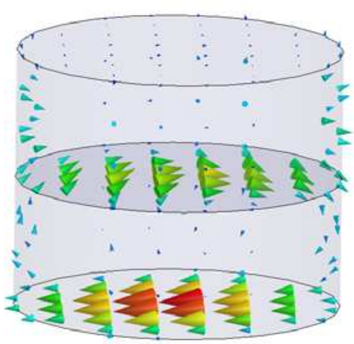

Figure 4. H-field of the second lowest order broadside mode in the first DR (the DR is mounted on the ground plane).

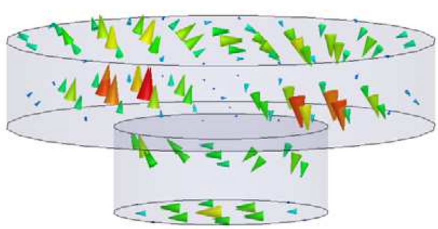

Figure 5. H-field of the second lowest order broadside mode in the second DR (the DR is mounted on the ground plane).

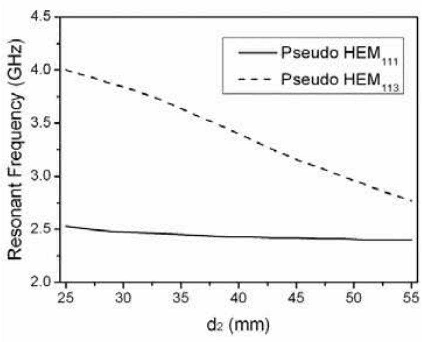

Figure 6. Resonant frequencies of the pseudo HEM_{111} and HEM_{113} modes of the one-step stair-shaped DR as a function of d_2 ($d_1 = 25\,\mathrm{mm}$, $h_1 = h_2 = 10\,\mathrm{mm}$).

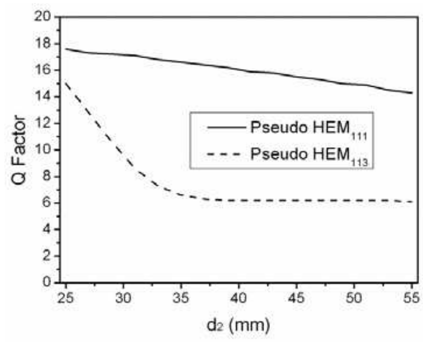

Figure 7. Q factors of the pseudo HEM_{111} and HEM_{113} modes of the one-step stair-shaped DR as a function of d_2 ($d_1 = 25\,\mathrm{mm}$, $h_1 = h_2 = 10\,\mathrm{mm}$).

the one-step stair-shaped DRA has a much wider bandwidth than the cylindrical DRA.

The H-fields of the second lowest order broadside mode of the two DRs are shown in Fig. 4 and Fig. 5, respectively. The resonant mode in Fig. 4 is HEM_{113} mode, and the resonant mode in Fig. 5 can be called pseudo HEM_{113} mode. The frequencies and Q factors of the pseudo HEM_{111} and pseudo HEM_{113} modes of the one-step stair-shaped DR as a function of d_2 ($d_1 = 25\,\mathrm{mm}$, $h_1 = h_2 = 10\,\mathrm{mm}$) are presented in Fig. 6 and Fig. 7, respectively. As shown in Fig. 6, the resonant frequency of the pseudo HEM_{113} mode decreases rapidly with the increase of d_2, while that of the pseudo HEM_{111} mode is not so sensitive with d_2. Form Fig. 7 the Q factors of the two modes decrease with the increase of d_2, it indicates that the bandwidth of the two modes both increase with the increase of d_2. So the frequency bands of the two modes can be merged by simply increasing the diameter of the top layer, thereby a wide bandwidth is obtained.

3. EXPERIMENTAL PROOF: A SLOT COUPLED ONE-STEP STAIR-SHAPED DRA

A prototype of the slot coupled one-step stair-shaped DRA was designed, fabricated, and measured to validate the theory proposed above. Fig. 8 shows the geometry of the slot coupled one-step stair-shaped DRA. The DR has a relative permittivity of 12. The dimensions of the one-step stair-shaped DR are $d_1 = 25\,\mathrm{mm}$, $d_2 = 50\,\mathrm{mm}$, and

$h_1 = h_2 = 10$ mm. The DRA is excited by a $50\,\Omega$ microstrip line through a rectangular slot. The slot is located at the center of the DRA, and it has a length of $l = 26$ mm and a width of $w = 3$ mm. The microstrip line ($w_f = 3$ mm) is etched on a 1.5 mm thick FR4 ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$) substrate, and it is terminated with an open circuited stub with length $l_f = 15$ mm. The ground plane has a size of $100 \times 100\,\text{mm}^2$.

The simulated (by HFSS) and measured return losses of the slot coupled one-step stair-shaped DRA are shown in Fig. 9. The measured impedance bandwidth ($S_{11} < -10$ dB) of the slot coupled one-step stair-shaped DRA is found to be 40% (2.25–3.38 GHz) which is wider

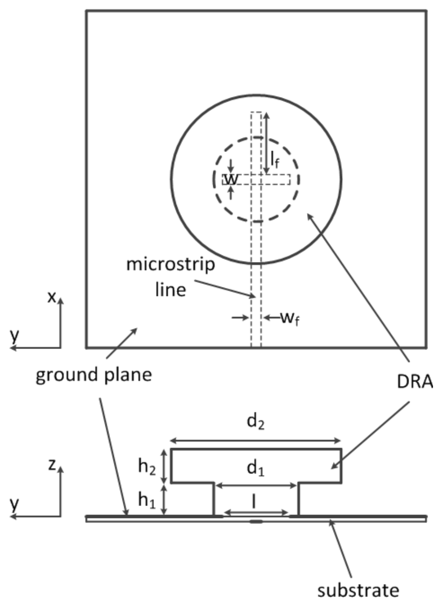

Figure 8. Geometry of the slot coupled one-step stair-shaped DRA.

Table 2. The resonant frequencies of the slot coupled one-step stair-shaped DRA and the one-step stair-shaped DR.

Resonant mode	Resonant frequency of the one-step stair-shaped DRA (Measured)	Resonant frequency of the one-step stair-shaped DR (Simulated)	Error (%)
Pseudo HEM_{111}	2.36 GHz	2.40 GHz	1.7
pseudo HEM_{113}	2.83 GHz	2.95 GHz	4.1

than the reported one-step slot-coupled stair-shaped DRA in [12]. Fig. 10 shows the simulated and measured input impedances of the slot coupled one-step stair-shaped DRA. There are two resonances within the frequency range of 2.0–3.4 GHz. The first resonance occurs at $f_1 = 2.36\,\text{GHz}$ and the second one occurs at $f_2 = 2.83\,\text{GHz}$. The measured resonant frequencies of the slot coupled one-step stair-shaped DRA and the simulated resonant frequencies of the one-step stair-shaped DR are summarized in Table 2. As shown in Table 2 f_1 is near the resonant frequency of pseudo HEM_{111} mode (with 1.7% error), and f_2 is near the resonant frequency of pseudo HEM_{113} mode (with 4.1% error). The discrepancy between the measured results and the simulated results may be caused by the introduction of the coupling slot on the ground plane.

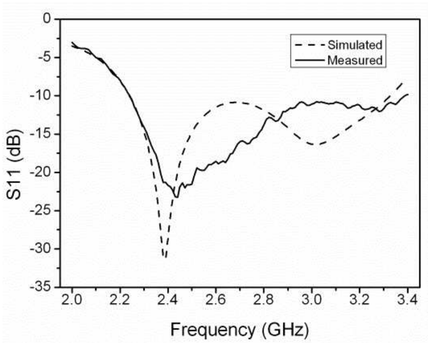

Figure 9. Simulated and measured return losses of the slot coupled one-step stair-shaped DRA.

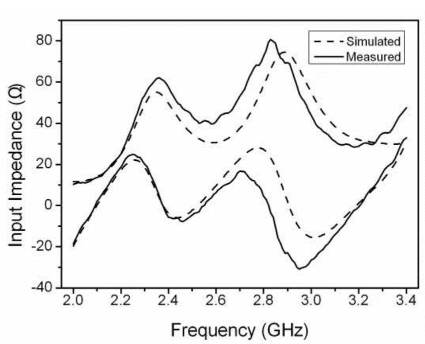

Figure 10. Simulated and measured input impedances of the slot coupled one-step stair-shaped DRA.

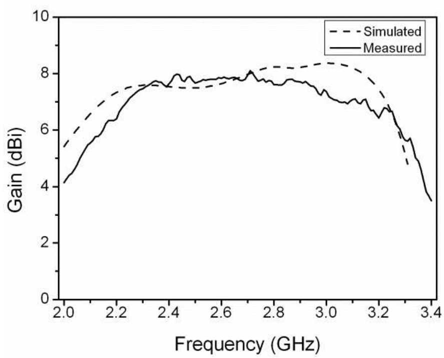

Figure 11. Measured gain of the slot coupled one-step stair-shaped DRA.

The simulated and measured antenna gain is shown in Fig. 11. With reference to the figure, the average gain is about 7.2 dBi across the impedance bandwidth. Fig. 12 shows the simulated and measured radiation patterns of the slot coupled one-step stair-shaped DRA at 2.3, 2.8, and 3.3 GHz. The antenna exhibits broadside radiation patterns across all of the impedance bandwidth. This indicates that the two resonant modes excited in the slot coupled one-step stair-shaped DRA at f_1 and f_2 are broadside modes, which correspond to the properties

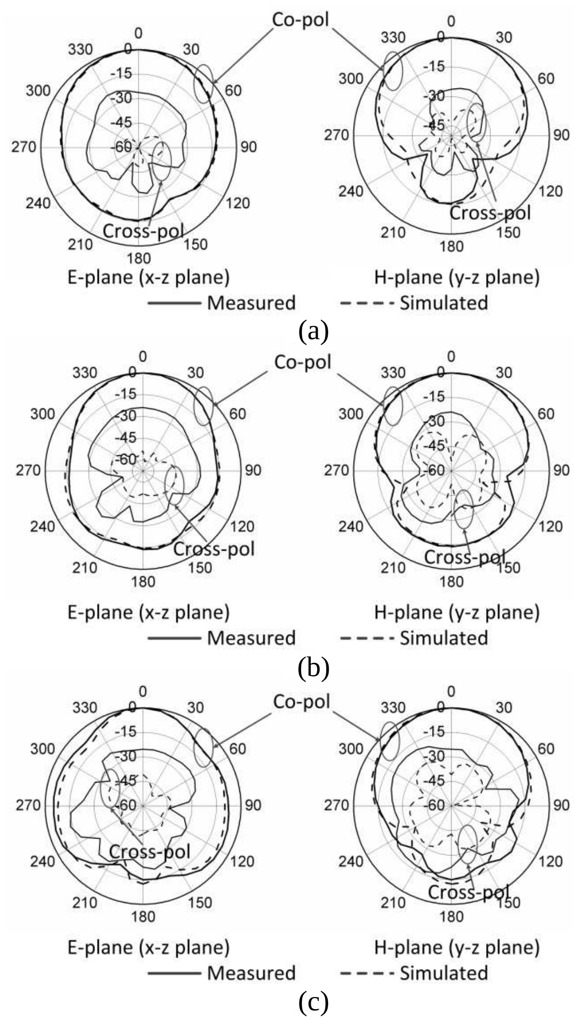

Figure 12. Measured radiation patterns of the slot coupled one-step stair-shaped DRA. (a) $f = 2.3$ GHz; (b) $f = 2.8$ GHz; (c) $f = 3.3$ GHz.

of the pseudo HEM_{111} and pseudo HEM_{113} modes.

The simulated and measured results of the proposed antenna demonstrate that the reason why the one-step stair-shaped DRA has a wide bandwidth is because two resonant modes (the pseudo HEM_{111} and pseudo HEM_{113} modes) are excited in the DRA.

4. CONCLUSION

The properties of the lowest two broadside modes of the one-step stair-shaped DR have been investigated in this paper. Based on the investigation, the reasons why the one-step stair-shaped DRAs have a wide bandwidth have been explained, and a prototype of the slot coupled one-step stair-shaped DRA has been designed to validate the proposed theory. It has been found that the reason why the one-step stair-shaped DRA has a wide bandwidth is because the pseudo HEM_{111} and pseudo HEM_{113} modes are excited in the DRA, and the bands of the two modes merge together when the dimensions of the DRA are properly chosen.

Future work will concentrate on increasing the bandwidth of the stair-shaped DRA by exciting other higher modes. The properties of the two-step stair-shaped DRA and coaxial probe fed stair-shaped DRA will be investigated.

REFERENCES

1. Long, S. A., M. McAllister, and L. C. Shen, "The resonant cylindrical dielectric cavity antenna," *IEEE Trans. Antennas Propag.*, Vol. 31, No. 3, 406–412, May 1983.
2. Zainud-Deen, S. H., H. A. El-Azem Malhat, and K. H. Awadalla, "A single-feed cylindrical superquadric dielectric resonator antenna for circular polarization," *Progress In Electromagnetics Research*, Vol. 85, 409–424, 2008.
3. Abdulla, P. and A. Chakraborty, "Rectangular waveguide-fed hemispherical dielectric resonator antenna," *Progress In Electromagnetics Research*, Vol. 83, 225–244, 2008.
4. Al-Zoubi, A. S., A. A. Kishk, and A. W. Glisson, "Analysis and design of a rectangular dielectric resonator antenna fed by dielectric image line through narrow slots," *Progress In Electromagnetics Research*, Vol. 77, 379–390, 2007.
5. Luk, K. M. and K. W. Leung, *Dielectric Resonator Antennas*, Research Studies Press, London, UK, 2003.
6. Rezaei, P., M. Hakkak, and K. Forooraghi, "Design of wide-band dielectric resonator antenna with a two-segment structure," *Progress In Electromagnetics Research*, Vol. 66, 111–124, 2006.

7. Rao, Q., T. A. Denidni, A. R. Sebak, and R. H. Johnston, "On improving impedance matching of a CPW fed low permittivity dielectric resonator antenna," *Progress In Electromagnetics Research*, Vol. 53, 21–29, 2005.
8. Huang, W. and A. A. Kishk, "Compact wideband multi-layer cylindrical dielectric resonator antennas," *IET Microw. Antennas Propag.*, Vol. 1, No. 5, 998–1005, Oct. 2007.
9. Huang, W. and A. A. Kishk, "Compact dielectric resonator antenna for microwave breast cancer detection," *IET. Microw. Antennas Propag.*, Vol. 3, No. 4, 638–644, Jun. 2009.
10. Chair, R., A. A. Kishk, K. F. Lee, and C. E. Smith, "Wideband flipped staired pyramid dielectric resonator antennas," *Electron. Lett.*, Vol. 40, No. 10, 581–582, May 2004.
11. Chair, R., S. L. S. Yang, A. A. Kishk, K. F. Lee, and K. M. Luk, "Aperture fed wideband circularly polarized rectangular stair shaped dielectric resonator antenna," *IEEE Trans. Antennas Propag.*, Vol. 54, No. 4, 1350–1352, Apr. 2006.
12. Chair, R., A. A. Kishk, and K.-F. Lee, "Wideband stair-shaped dielectric resonator antennas," *IET Microw. Antennas Propag.*, Vol. 1, No. 2, 299–305, Apr. 2007.
13. Buerkle, A., K. Sarabandi, and H. Mosallaei, "Compact slot and dielectric resonator antenna with dual-resonance, broadband characteristics," *IEEE Trans. Antennas Propag.*, Vol. 53, No. 3, 1020–1027, Mar. 2005.
14. Chair, R., A. A. Kishk, and K. F. Lee, "Wideband simple cylindrical dielectric resonator antennas," *IEEE Microw. Wireless Compon. Lett.*, Vol. 15, No. 4, 241–243, Apr. 2005.
15. Li, B. and K. W. Leung, "Strip-fed rectangular dielectric resonator antennas with/without a parasitic patch," *IEEE Trans. Antennas Propag.*, Vol. 53, No. 7, 2200–2207, Jul. 2005.
16. Almpanis, G., C. Fumeaux, and R. Vahldieck, "The trapezoidal dielectric resonator antenna," *IEEE Trans. Antennas Propag.*, Vol. 56, No. 9, 2810–2816, Sep. 2008.
17. Fang, X. S. and K. W. Leung, "Designs of single-, dual-, wide-band rectangular dielectric resonator antennas," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 6, 2409–2414, Jun. 2011.
18. Fang, X. S. and K. W. Leung, "Linear-/circular-polarization designs of dual-/wide-band cylindrical dielectric resonator antennas," *IEEE Trans. Antennas Propag.*, Vol. 60, No. 6, 2662–2671, Jun. 2012.