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Author's Reply

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The authors appreciate the investigation and comments by T. J. Ellis regarding the quasi-Yagi antenna. In fact, one of the co-authors (Y. Qian) has been challenged multiple times in the past on the novelty of the quasi-Yagi antenna and feels obliged to take this opportunity to make some clarifications and re-emphasize the uniqueness of this particular antenna structure.

We were definitely aware of the original publications by Edward and Rees [1], which we believe is great work. The difference of the quasi-Yagi structure, however, is really not just adding a printed director element. It is more fundamentally related to the surface wave behavior in the substrate. As a result, the two antennas belong to two different categories. In the E plane, the antenna by Brian and Rees is bi-directional, while the quasi-Yagi is "end-fire" by itself, without the need of extra reflectors.

As is well known, an ideal half-wavelength dipole radiates evenly to the front and back sides in the E plane. A printed dipole on electrically very thin substrate will have similar behavior, because the substrate in this case is mainly for the purpose of supporting the printed dipole and feeding circuitry. In the broadband printed dipole invented by Edward and Rees, a novel feeding structure based on a microstrip-to-slot transition was used cleverly to obtain broadband impedance matching for the printed dipole. However, the antenna operates in a similar manner as a normal dipole, without major surface wave phenomenon involved. As a result, to obtain good front-to-back ratio, the authors used a fairly large metal reflector perpendicular to the printed dipole. This is common practice to obtain unidirectional radiation patterns out of a dipole, whether printed or not.

The original Yagi-Uda dipole antenna is a work of genius, because it replaces the otherwise large and clumsy reflector with simple wires which are just slightly longer (reflector) and shorter (director) than the dipole itself, while delivering similar level of unidirectional radiation pattern. It is also noticed that a Yagi-Uda can maintain decent front-to-back ratio without any director elements, but the presence of the reflector is essential to turn a low-directivity dipole into an end-fire antenna.

If we consider the diameter of the reflector wire in a Yagi-Uda and come up with an effective area of the "reflector," we can easily appre-

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ciate the significance of the Yagi-Uda concept because it shrinks the size of a normal reflector by orders of magnitude.

In the case of our quasi-Yagi antenna, this effective area of the reflector is essentially reduced to "zero," if we just focus on the metallic structure and assume perfect conductor with zero thickness. Nevertheless, the antenna still delivers decent levels of front-to-back ratio, as well as polarization purity across the entire impedance bandwidth. No reflector was used in our antenna measurements, as contrary to the work of Edward and Rees. In some cases we even tried to eliminate the effect of the SMA connectors by feeding the antenna from under the substrate using a feedthrough pin and saw no effect on the radiation patterns.

This finally leads us to the topic of surface wave. The dielectric substrate thickness of the quasi-Yagi antenna was chosen in such a way that it is thick enough to allow a significant amount of surface wave (TE_0) to be launched into the bare-slab portion of the antenna, but still within the cutoff for TE type surface wave in the single-sided metallized slab portion. The truncated ground plane of the microstrip feeding structure provides the boundary of these two portions and is the most critical design parameter. Because of the cutoff of the TE mode at the ground plane truncation, the electromagnetic energy is forced to be launched into the end-fire direction.

In order to clarify that there is indeed a dependence on surface wave energy for the fundamental operation of the quasi-Yagi antenna, we present some numerical simulation results. Fig. 1 shows E-plane antenna radiation patterns simulated using our proven FDTD code. We compare the radiation patterns of the original quasi-Yagi antenna [2], the quasi-Yagi with the director element removed, the original antenna with the substrate under the dipole portion of the antenna removed (replaced with $\varepsilon_r = 1$), the case with the substrate under the dipole portion of the antenna removed and the director element also removed, and finally a thin dielectric material with $\varepsilon_r = 2.33$ replaced under the dipole region. The results show that with no substrate under the dipole there is no front-to-back ratio to speak of. Also the effect of the director is nonexistent compared to the director's effect on the original quasi-Yagi design. When a thin low epsilon material is placed under the dipole region only a minimal front-to-back ratio is present, as expected. This clearly shows that surface wave influences and in fact contributes to the antenna's radiation characteristics.

Ellis' conclusion that there is only weak surface wave inside the quasi-Yagi structure is based on two investigations: 1) the directivity does not change significantly by changing the substrate thickness and (2) the directivity changes very little when the distance from the director to the substrate edge is reduced. The two sets of simulations are not convincing evidence to deny the role of surface waves here.

1) Ellis' HFSS simulations indicates that by changing the substrate thickness by $+/-20\%$ from the nominal design, the radiation patterns of the quasi-Yagi remains the same and directivity only changes by 0.3 dB. This result by itself does not tell any information about the surface wave. As long as the substrate is within a reasonable range of thickness to operate the way it is intended, the radiation pattern should remain similar, as supported exactly by the above FEM simulations. If, however, the substrate thickness is changed to extremely small or large values, the radiation patterns should start degrade, as found by extensive FDTD simulations by the authors.
2) The sensitivity of radiation patterns with distance from the director to the substrate edge needs some clarification. For the case of an ideal TE mode, the electric field component is parallel to the substrate edge and should experience a smooth transition to free space even though the dielectric constant is relatively high ($\varepsilon r = 10.2$). This explains why no significant change in directivity is observed in Ellis' simulations – ideally it should not change no matter where one terminates the substrate in front of the director. The insensitivity indicated in the HFSS simulations does not imply in any way that there is no or little surface wave inside the substrate. In realty, meanwhile, if the substrate is truncated very close to the antenna radiators including the director, there will be some field components normal to the edge and cause some reflections. This is consistent with our experimental observations. This sensitivity issues becomes noticeable mainly in very high-frequency (millimeter-wave) versions of the quasi-Yagi structure, where the short wavelength poses more challenges in test.

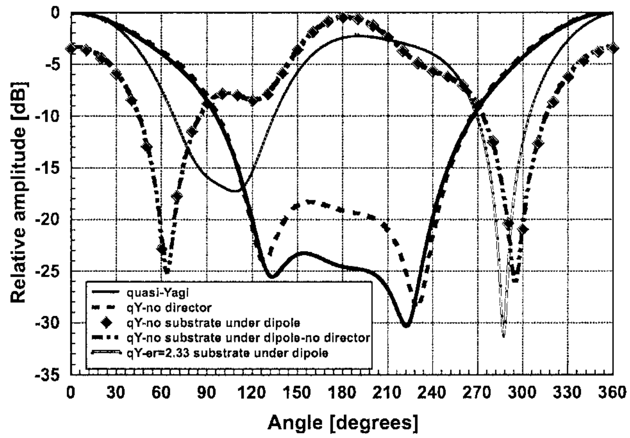

Fig. 1. FDTD simulated E-plane radiation patterns (end-fire $= 0°$).

In conclusion, we regretfully disagree with Ellis' claim that there is little surface wave effect in the quasi-Yagi antenna, because the HFSS simulation results provided are of little relevance and do not provide convincing evidence to that suggestion. We also disagree with his comments that the quasi-Yagi is essentially the same at the printed dipole by Edward and Rees. They operate in entirely different principles. The latter relies on a reflector to achieve directivity. The quasi-Yagi utilizes TE surface wave cutoff at the truncated ground plane of the microstrip feeding network to realize end-fire radiation. It is based on a concept similar to the original Yagi-Uda antenna, but with "zero thickness reflector" in terms of metal cross section in the backside direction. The role of the surface wave in this structure is significant and undeniable, although more in-depth work is needed to better quantify its effect, either experimentally or theoretically. The authors welcome any further investigations and insights into this structure.

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