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Advanced Figure of Merit for the Evaluation of OAM Modes for Communication Applications

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Abstract

Orbital Angular Momentum Multiplexing (OAM) is a proposed solution to increase the data-rate of wireless communication links. Here, the orthogonality of OAM modes is used for propagation in free space so that existing frequency bands can be occupied by multiple orthogonal OAM in parallel without signal interference. We report on a novel approach for a figure of merit to describe the mode purity of OAM antennas for realistic antenna evaluation. In comparison to the classic analysis of the OAM mode quality along the ring of maximum purity and single elevation, the 3 dB bandwidth of the antenna, which is important for real-world communication applications, is taken into account.

1. Introduction

The amount of data transferred by wireless communication systems is ever increasing, leading to many innovations, including the use of new frequency bands and more complex modulation schemes [1,2]. Nevertheless, the available frequency spectrum for wireless communications in the microwave domain is still scarce and technology development for new mm-wave and THz bands is heavily demanding. One approach to use existing frequency bands more efficiently is spatial multiplexing, e.g. via the use of multiple polarizations. An extension of this concept is the use of so called Orbital Angular Momentum (OAM) waves, a vortex wave with, in theory, unlimited orthogonal modes which would not interfere with each other within the same frequency band [3,4]. Such waves have been successfully demonstrated in optical fibers and free-space applications, with high mode purities and sufficient mode isolation for practical purposes [5]. But there are also critical voices, discussing the real-world consequences of intrinsic divergent beam shapes, the amount of cross-talk, and demultiplexing and the required signal strengths [6]. Additionally, often only a single frequency is discussed in publications, strongly limiting the usefulness of the results for communication applications. Furthermore, the OAM mode is often only evaluated at a single ring with the highest purity, which only caries a fraction of the energy [7].
Here, we introduce an extension of the conventional figure of merit (FoM) for OAM antennas and demonstrate the use in optimization of helical antennas, simulated with CST. The advantages of the newly introduced advanced OAM FoM is demonstrated and its implications for wireless communications is discussed.

2. Advanced OAM Figure of Merit

For the evaluation of OAM antennas in literature, commonly the "donut-shape" of a vortex wave is shown, similar to Figure 1a, in combination with the corresponding phase-front, such as depicted in Figure 1b. If there is not only a qualitative evaluation of the OAM Mode, but also quantitative one, the normalized mode purity along a "ring" at a single elevation, indicated by the dashed line in Figure 1a, is calculated. For the application in wireless communication systems, however, it is common to consider properties such as the gain of an antenna over its entire 3 dB bandwidth. This range is given in Figure 2 for both the radiation pattern and the phase pattern and is limited by the solid lines in the respective images. It can already be seen from these figures that the gain and phase partially change significantly when the elevation angle is changed. We therefore suggest that the 3 dB bandwidth should also be applied to the evaluation of the mode purity.

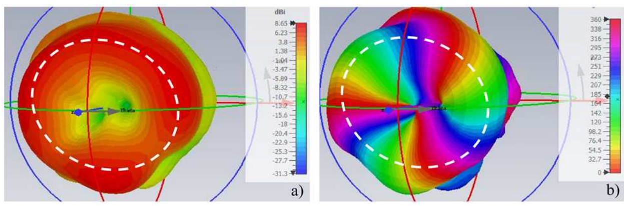

Figure 1. The typical donut-shaped 3D radiation pattern of a simulated vortex wave radiated by a helical antenna is shown in a). Here, the white dashed line represents the ring that is normally used to indicate the mode purity for a single elevation angle. Additionally, the corresponding phase pattern is shown in b) highlighting the same single elevation angle.

The gain of single OAM mode along the whole azimuthal 360° for an angle of a single elevation is given by

$$J_l = \frac{1}{2\pi}\int_0^{2\pi} \tilde{E}(r,\Theta,\phi)\mathrm{e}^{-\mathrm{j}l\phi}\,\mathrm{d}\phi \qquad (1).$$

Hereby J_l is the gain of the antenna for a given mode l, which is defined by the integral of the electrical field $\tilde{E}$ as a function of its spehrical coordinates (r, Θ, ϕ).

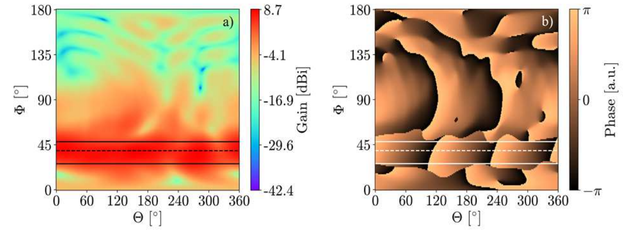

Figure 2. In a) the 2D representation of the vortex wave from Figure 1 a) is given. As an extension to the already introduced indication of the single elevation angle by a dashed line, the 3 dB bandwidth of the antenna is represented here by the two solid lines. In b) the corresponding phase pattern and its 3 dB bandwidth is given.

A normalization can be applied to show which share of the total energy W is carried by a single mode l within the range of relevant modes $|l_{max}|$ according to equation (2).

$$W = \frac{|J_l|}{\sum_{-l_{max}}^{l_{max}} |J_l|}, -l_{max} \leq l \leq l_{max} \quad (2).$$

To finally account for the full 3dB range, the normalised energy has to be integrated over the corresponding elevation range defining the advanced figure of merit $FoM_{3\text{dB}}$ as formulated in equation (3)

$$FoM_{3\text{dB}} = \int_{\Theta_{3\text{dB,min}}}^{\Theta_{3\text{dB,max}}} \frac{\left|\frac{1}{2\pi}\int_0^{2\pi} \tilde{E}(r,\Theta,\phi)\mathrm{e}^{-\mathrm{j}l\phi}\mathrm{d}\phi\right|}{\sum_{-l_{max}}^{l_{max}}\left|\frac{1}{2\pi}\int_0^{2\pi} \tilde{E}(r,\Theta,\phi)\mathrm{e}^{-\mathrm{j}l\phi}\mathrm{d}\phi\right|}\,\mathrm{d}\Theta \quad (3)$$

An analysis along the dashed line – as it would typically be carried out – is depicted in Figure 3 a) showing that mainly a mode order of $l = -3$ is detected with high purity. In comparison, Figure 3 b) shows the evaluation along the lower edge of the 3 dB band as indicated in Figure 2 by the solid line. From the comparison of both figures it can be seen that other mode orders now also have a clear influence and the previously existing dominance of mode $l = -3$ is completely lost. This already indicates that the evaluation of a single ring within the 3 dB range cannot describe the mode purity over its entirety.
Thus, we have applied the approach described in Equation (3) so that a better picture can be obtained. The result is shown in Figure 3 c) and confirms the previous statement regarding mode purity, if the range relevant for a more application-oriented consideration as for example communications is taken into account.
Moreover, it also indicates that it is fairly easy to mistake an antenna for a good OAM antenna, based on the evaluation of just a single ring and justifies the use of the introduced $FoM_{3\text{dB}}$ when OAM antennas are to be evaluated for a real-life application such as communications. In the next section, we will discuss how $FoM_{3\text{dB}}$ is used to optimize helical antennas.

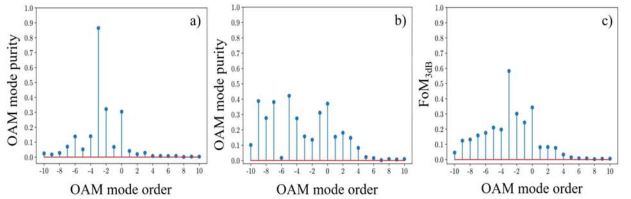

Figure 3. Mode purity as a function of the OAM mode order. In a), an analysis is performed along the dashed line in Figure 2a), showing that the mode $l = -3$ is the dominant mode. In b), the analysis is shown at the lower edge of the 3 dB range. In c) the result for the $FoM_{3\text{dB}}$ is given. This visualizes that an antenna might be evaluated positively for use in OAM applications when only taking a single ring into account, while actually the majority of the energy is carried over in undesired modes, resulting in significantly lower channel isolation.

3. Parameter optimisation for high bandwidth OAM helical antennas

In order to be able to verify the introduced method of evaluating the mode purity, helical antennas were first designed on the basis of simulations using CST. Hereby, criteria on a theoretical level and those that are relevant for later practical realization were considered. For a transmission link application, the aim is for the helical antenna to emit its energy in a forward direction, i.e. to operate in so-called axial mode. This means that the circumference of the antenna ($\pi \cdot D \approx \lambda$) must correspond to the operating wavelength to be emitted. Otherwise, if this is smaller than the wavelength, a normal mode is emitted [8].
In addition, if an OAM mode is to be emitted by the antenna, the condition of the helix circumference must be adapted to the corresponding mode order. This results in an axial emitted vortex wave with $\pi \cdot D \approx \lambda \cdot l$ [9].

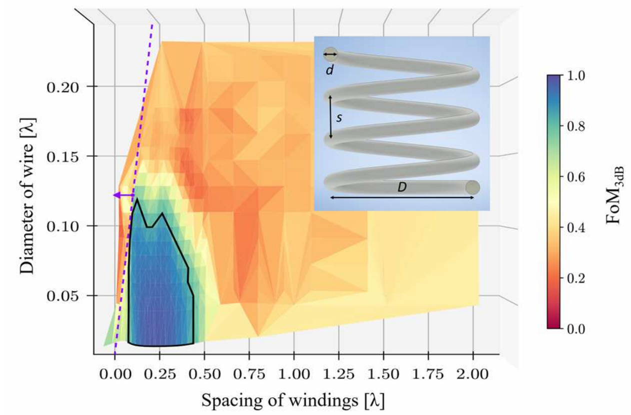

Figure 4. Mesh plot of the OAM $FoM_{3\text{dB}}$ optimized for the emission of an OAM mode $l = -3$ at 275 GHz as a function of the spacing of the windings (s) as well as the diameter of the helical wire (d). As an inset a schematic of the helical antenna with its parameters is given. For values left of the dashed purple line the helix fuses to a cylinder with solid walls, as the spacing is too small for the diameter.

In addition to the diameter (D), a helical antenna is defined primarily by its spacing (s) and its wire diameter (d). The wire diameter is relevant as it is in the order of magnitude of the wavelength in the case considered here and is therefore no longer an infinitesimal, i.e. negligible, parameter. The influence on the $FoM_{3\mathrm{dB}}$ of each parameter is shown in Figure 4 for a given OAM mode $l = -3$.
Besides the $FoM_{3\mathrm{dB}}$, the boundary at which the windings of the helix would merge is marked in purple. Additionally, the area that achieves an $FoM_{3\mathrm{dB}} \geq 0.85$ is framed in black which was evaluated as a threshold for a good OAM purity.
In communication applications in general, the broadband capability of the antenna plays a decisive role. If the application is now extended using OAM, the frequency range of the $FoM_{3\mathrm{dB}}$ also has to be accounted, as otherwise the multiplex approach cannot be exploited.
We have therefore investigated both the frequency and the $FoM_{3\mathrm{dB}}$ bandwidth of the antenna. In the range of 240 to 290 GHz a $FoM_{3\mathrm{dB}} \geq 0.85$ is achieved indicated by the black dotted line in Figure 5. As can be seen, the gain maintains a reasonable level of over 7 dBi in this range.

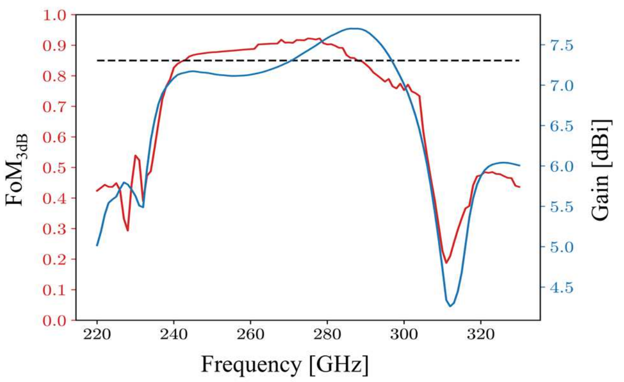

Figure 5. OAM FoM and antenna gain shown over frequency. In the range between 240 GHz and 290 GHz, the $FoM_{3\mathrm{dB}}$ is above a value of 0.85 while the antenna gain is >7 dBi for the mode l = -3.

4. Influence on mode purity due to fractional signal reception

Mode purity was also considered from the perspective of a receiver. Here the particular focus was on the influence on the mode purity if the entire azimuthal range of the transmitted signal cannot be detected. This is shown in the figure for three different angular ranges. Initially, when evaluating a full circle (ϕ = 360°), a clear dominance of the mode l = -3 can be recognized. However, if only 320° of the azimuthal angle is covered, a considerable increase in the secondary modes is already recognizable. A further reduction (ϕ = 180°) of the azimuthal range finally reveals a complete loss of the expected mode dominance.
This has a particular influence if the transmitter antenna does not have highly directive properties. Without further focusing the antenna's beam on one spot, it is thus not possible to state on the mode used from the receiver side.

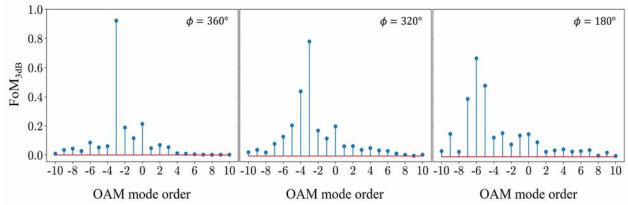

Figure 6. Degradation of the mode purity when receiving with a reduced azimuthal angle area. A reduction of 40° compared to the full circle already has a noticeable influence of secondary modes. The dominance of the emitted mode is completely lost when the azimuthal angle range is further reduced.

5. Conclusion

To summarize, we have shown that the advanced $FoM_{3\mathrm{dB}}$ presented here can provide improved information about the mode purity of OAM antennas for application-oriented applications. In contrast to the common consideration of just a single elevation angle the advanced criterion is taking the complete 3 dB bandwidth of an antenna into account. Moreover, the $FoM_{3\mathrm{dB}}$ is applied to optimize the geometries of a helical antenna – such as its diameter, and spacing of the windings as well as the diameter of the wire – in the WR3.4 frequency range. As a result, the optimized antenna offers a bandwidth of 50 GHz (240 GHz - 290 GHz) while maintaining a high mode purity within the whole bandwidth.

6. Acknowledgements

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