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Research Article

Analysis of Cross Polarization in Optical Systems

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Abstract – The objective of this study is to investigate the effects of angle of incidence and off-axis angle on the cross-polarization of a Gaussian beam. The phenomenon of cross-polarization pertains to the alteration in the polarization of electromagnetic waves resulting from reflection, refraction, or scattering during propagation. In optical systems, the suppression of cross-polarization is a crucial aspect that must be addressed to ensure the quality and performance of the signal. The phenomenon of cross-polarization has a significant impact on telecommunication, radar, and optical imaging. It can lead to signal loss and higher error rates, which in turn affects system reliability and data accuracy. This research will provide theoretical support to help devices maintain the ability to make accurate measurements to maintain the desired polarization state, thereby improving the operational reliability of optical systems and ensuring high-quality signal transmission and accurate imaging in modern optical systems.

Keywords –Cross Polarization; Distortion; Electromagnetic Waves; Gaussian Beam; Optical Systems.

I. INTRODUCTION

Quasi-optical techniques are widely used in modern communications and radar systems. These systems typically use Gaussian beams as the primary transmission mode to ensure efficient and low-loss signal transmission. In such systems, reflective focusing elements (e.g., mirrors and lenses) are often used to control the path and characteristics of the beam. However, the use of reflective focusing elements can have a significant effect on the polarization state of the incident beam, which in turn affects the overall performance of the system.

Polarization is one of the most important characteristics of electromagnetic waves and describes the direction of oscillation. In an ideal situation, the direction of vibration of a linearly polarized beam remains constant. In practice, however, changes in the surface curvature and local normal direction of the reflecting focusing element can cause the direction of polarization to change. This phenomenon, i.e. the change in polarization direction due to reflection or transmission, is called cross-polarization.

The phenomenon of cross-polarization is particularly important in antenna design because the polarization characteristics of an antenna directly affect the quality of signal transmission and reception. In quasi-optical systems, the off-axis configuration of the reflective focusing element often leads to significant cross-polarization effects. This phenomenon not only reduces the transmission efficiency of the system, but can also introduce unexpected noise and interference, potentially affecting signal accuracy. In order to investigate the factors affecting cross-polarization, many scholars have conducted theoretical analyses and experimental studies. Many factors have been identified as potentially affecting cross-polarization, including Gaussian beam patterns, Gaussian-Elmer polynomials, surface curvature of the reflecting elements, off-axis angle, angle of incidence, and the relationship between focal length and beam radius. The results of these studies contribute to a more complete understanding of the cross-polarization phenomenon, leading to optimization of the design of reflective focusing elements, reduction of cross-polarization effects, and improvement of system performance.

The study of methods to mitigate the effects of cross-polarization is a comprehensive and far-reaching field of inquiry. This paper presents a review of the literature on cross-polarization. The following section presents a summary and evaluation of the literature.

According to [1], the study of cross- polarization focuses on how reflective focusing elements affect the polarization state of incident Gaussian beams. The research shows that changes in the surface curvature and normal direction of the reflector can alter the polarization direction of a linearly polarized beam. In systems with off-axis reflectors, cross-polarization effects often do not cancel out, requiring calculation through integration over the illumination pattern. Both theoretical and experimental studies demonstrate that Gaussian beam models can accurately predict cross-polarization and optimize system design. To mitigate cross-polarization, the study recommends using symmetrical designs and strict design standards to reduce its levels. This research highlights the importance of managing cross-polarization in complex optical systems, particularly in fields requiring precise polarization control, such as telecommunications and astronomy. Future directions include developing more sophisticated real-time compensation models and integrating AI for dynamic polarization control.

Yeap and Tham in [2, 3] optimized offset receiver optics for radio telescopes, the research addresses how cross-polarization can be managed through careful optics design. The study focuses on the Cassegrain antenna system used in the Atacama Large Millimeter Array (ALMA), where the use of offset feeds and ellipsoidal mirrors can lead to cross-polarization issues. To optimize performance, the design incorporates multimode Gaussian optics to minimize cross-polarization by adjusting the edge taper and alignment of components. The research demonstrates that maintaining precise alignment and using symmetrical designs significantly reduce cross-polarization, enhancing overall antenna efficiency. This study highlights the importance of detailed optics design in achieving high aperture efficiency and effective polarization control in radio telescopes.

Dragone study offset multireflector antennas in [4]. He focused on reflector antennas that could achieve excellent cross-polarization discrimination. The research outlines conditions that ensure circular symmetry and the absence of cross-polarization in the far field of an antenna when using a suitable feed, such as a corrugated horn. By aligning the feed's axis orientation properly, it is possible to maintain symmetry and eliminate cross- polarization, even in systems with multiple reflectors. This is crucial in radio systems where orthogonal polarizations double transmission capacity. The study suggests that combining multiple reflectors can achieve this goal by maintaining the polarization of the feed excitation throughout the antenna's far field. The research provides design criteria that are valuable for reducing cross-polarization and enhancing antenna performance, particularly in multibeam applications where polarization purity is essential (Dragone, 1978).

Aboserwal et al. [5] present a comprehensive analysis of the comments on the definition of cross-polarization. The researchers offer a detailed comparison between the second and third definitions of Ludwig's cross-polarization, as applied to a line-polarized antenna. This analysis is supported by experimental evidence. The findings indicate that the second definition of Ludwig results in a reduced level of cross-polarization compared to the third definition for x- or y-polarized current sources in the diagonal plane. In light of these findings, new polarization bases are proposed, with the source serving as a reference point and the orientation of the source in the yz plane taken as the basis for comparison. Additionally, the analysis of several real antennas for diverse applications is presented. In light of the proposed polarization formulas, a comprehensive investigation is conducted into the numerical and measured radiation direction diagrams for wire and printed dipoles, rectangular patches, cone angle, and open rectangular waveguide antennas. The employment of dual-polarized components and dual-polarized active phased arrays is encouraged for applications involving broadside radiation. Polarization diversity techniques permit the transmission of two independent signals using a single frequency band. In such systems, the degree of isolation between channels is contingent upon the extent of cross-polarization suppression. High cross-polarization levels result in a degradation of the quality of orthogonal signals due to mutual interference. It is therefore crucial to achieve pure polarization with the lowest possible cross-polarization level.

Nevertheless, despite the theoretical assumption that the orthogonally polarized channels are completely isolated, the design of a system with extremely low cross-polarization levels in the coverage area remains a challenging endeavor. A detailed comparison of the second and third definitions of cross polarization as proposed by Ludwig was presented in [5]. To illustrate the concept, experiments were conducted using linearly polarized antennas. The findings indicate that the second definition of Ludwig results in a reduced level of cross-polarization compared to the third definition for x- or y-polarized current sources in the diagonal plane. In light of these considerations, novel polarization bases are put forth, with the source serving as a reference point and the orientation of said source in the yz plane. Additionally, the analysis of several real antennas for diverse applications is presented. In light of the proposed polarization formulas, a detailed investigation is conducted into the numerical and measured radiation direction diagrams for wire and printed dipoles, rectangular patches, cone angle, and open rectangular waveguide antennas. The employment of dual-polarized components and dual-polarized active phased arrays is encouraged for applications involving broadside radiation. Polarization diversity techniques permit the transmission of two independent signals using a single frequency band. In such systems, the degree of isolation between channels is contingent upon the extent of cross-polarization suppression. High cross-polarization levels result in a degradation of the quality of orthogonal signals due to mutual interference. It is therefore important to achieve pure polarization with the lowest possible cross-polarization level.

Nevertheless, despite the theoretical assumption of complete isolation between orthogonally polarized channels, the practical design of a system with extremely low cross-polarization levels within the coverage area remains a significant challenge [5].

The aim of this study is to provide a comprehensive analysis and synthesis of the main factors affecting cross-polarization and to validate the theoretical model through experimental verification. Through the in-depth study of these factors, we aim to provide a theoretical basis and practical guidance for the design of reflective focusing elements in quasi-optical systems, thereby promoting the development of more efficient and reliable communication and radar systems. Quasi-optical techniques are widely used in modern communication and radar systems. These systems typically use Gaussian beams as the primary transmission mode to ensure efficient and low-loss signal transmission. In such systems, reflective focusing elements (e.g., mirrors and lenses) are often used to control the path and characteristics of the beam. However, the use of reflective focusing elements can have a significant effect on the polarization state of the incident beam, which in turn affects the overall performance of the system.

II. CROSS POLARIZATION

According to [1], the vectorial properties of the field in Gaussian beams used in quasi-optical systems have so far been neglected. To fully characterize the reflective focusing elements, the effect of these elements on the polarization of the incident beam must be considered, with the beam still being treated as transversely polarized in the direction of propagation. Cross-polarization is defined as a state of polarization used to describe, for example, how the feed of an antenna is changed. A definition that includes the effect of any focusing element on the polarization state of an incident Gaussian beam is adopted.

Typically, changes in the curvature of the surface of a reflective focusing element and in the direction of the local surface normal result in the polarization direction of the linearly polarized incident beam being altered. In certain cases, such as when an axisymmetric antenna is illuminated by a beam propagating along its axis, the cross-polarization components are canceled at the axisymmetric point. For the more commonly used off-axis reflective focusing elements, the cross-polarizations are not typically canceled and must be calculated by performing integration over the illumination pattern of the reflector. The general case of quadratic reflectors (which produce a quadratic phase shift) has been studied by [6] and [7], and the case of offset parabolic reflectors has been analyzed in detail by [8].

Considering an incident beam in TEM00 mode, an x-polarized component, denoted as E01, is contained in the reflected beam when the incident beam is linearly polarized in the y-direction, and a y-polarized component, denoted as E10, is contained when the polarization is initially in the x-direction. In all cases, the cross-polarized component is found to be in phase with the co-polarized component in the reflector aperture.

The power fraction of the incident beam that is reflected in the cross-polarized component is provided by [7] as shown in (1)

$$K_{CO} = 1 - 2U = 1 - \frac{{W_m}^2}{4f^2}\tan^2(\theta_i) \tag{1}$$

As a result, it is observed that the power loss caused by cross-polarization is twice that caused by beam aberrations, and the cross-polarization can be kept relatively low. However, the relative importance of beam distortion and cross-polarization is found to depend on the overall utilization of the system.

In this analysis, the total power of the cross-polarized modes is considered, but it is also possible for the peak relative field amplitude to be determined directly. Since the different modes of the Gauss-Hermite beam are normalized to a unit power flux, equal mode amplitudes are implied to result in equal power fluxes. From (2), it is shown that the relative mode amplitude of the co-polarized beam is given by:

$$C_{x-pol} = \frac{\tan\theta_i}{2}\left(\frac{W_m}{f}\right) \tag{2}$$

The aim of this project is to model and analyze (1) and (2). Control variable methods are chosen based on the factors in the formula, and variables are constantly changed to observe the impacts of these factors. Multiple groups of variables are designed for comparison to perform a multi-dimensional analysis.

III. RESULTS AND DISCUSSION

Equation (1) provides a direct measure of the energy loss due to cross-polarization, indicating the efficiency of the system in maintaining the ideal state of polarization. The metric K_{co} quantifies the proportion of energy in the incident beam that is reflected by the cross-polarized component. The closer the value is to 0, the higher the cross-polarization, indicating that more energy is lost to cross-polarization.

Figure 1 shows the relationship between K_{co} and f when the angle θ_i varies from 15° to 180°, and beam radius W_m = 100 mm. It can be seen from the figure that as f increases, K_{co} gradually increases to a value close to 1.

Figure 2 shows the relationship between K_{co} and f when W_m varies from 0.1 mm to 1.0 mm and angle θ_i is fixed at 60°. It can be seen that as f increases, K_{co} gradually increases towards 1. Also, the larger is the value of W_m, the larger is the range variation between of K_{co} and f.

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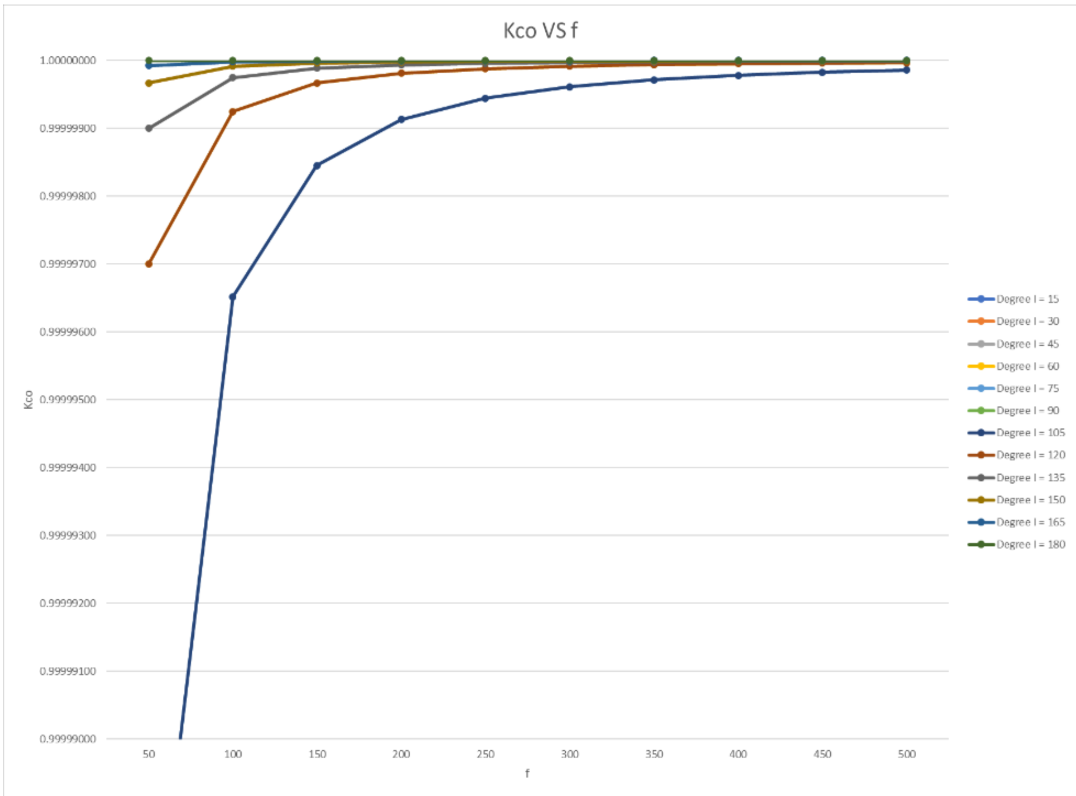


Fig. K_{co} vs f with θ_i varies from 15º to 180º

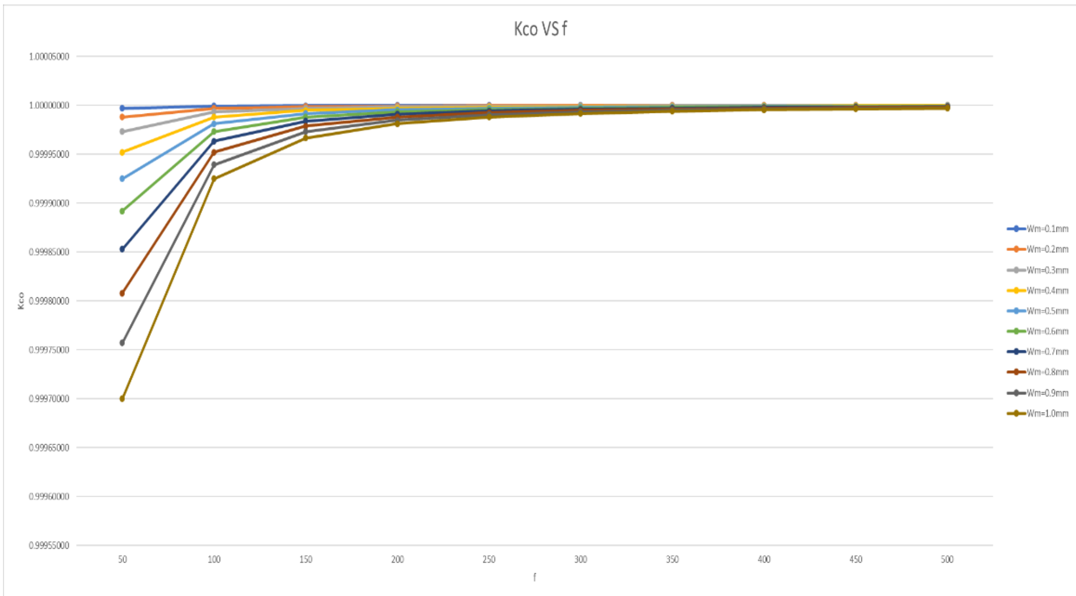


Fig. 2 K_{co} vs f with θ_i with W_m varies from 0.1 mm to 1.0 mm

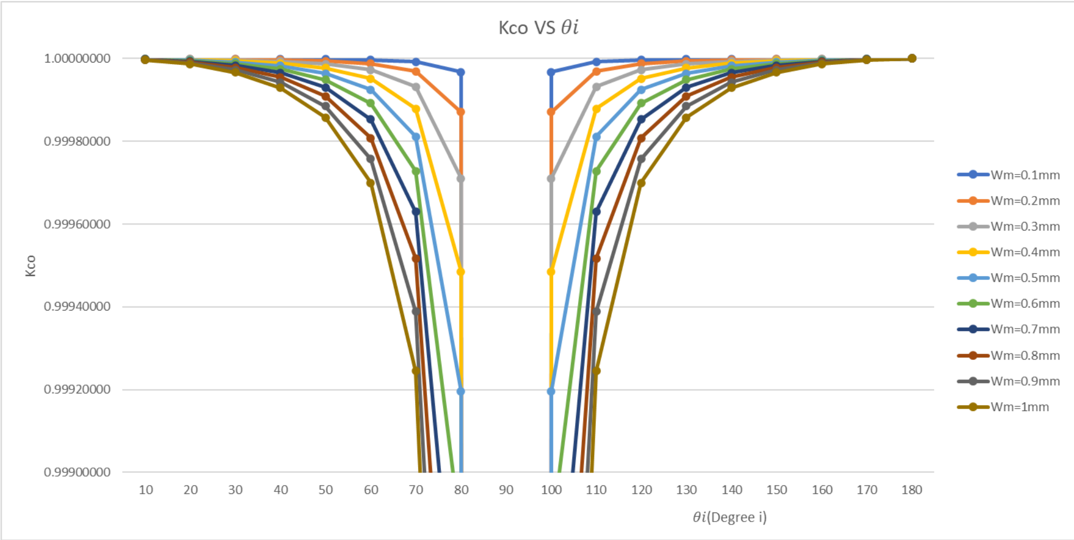


Fig. 3 K_{co} vs θ_i with W_m varies from 0.1 mm to 1.0 mm

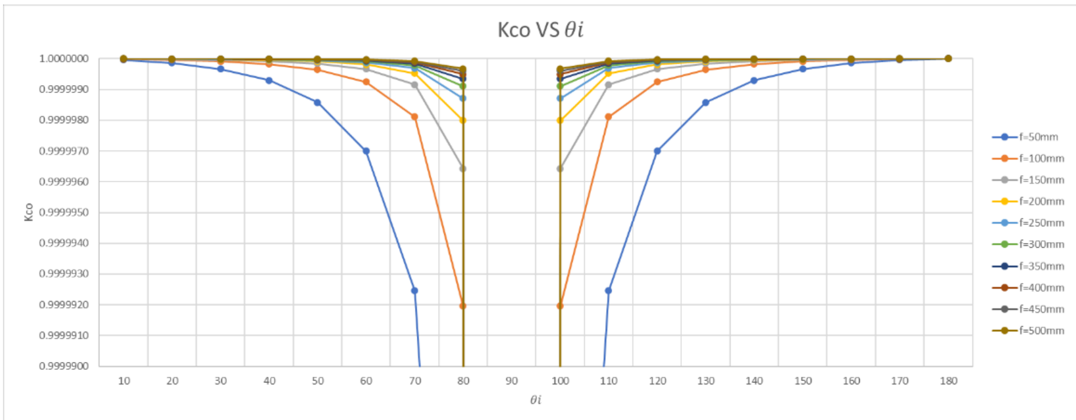
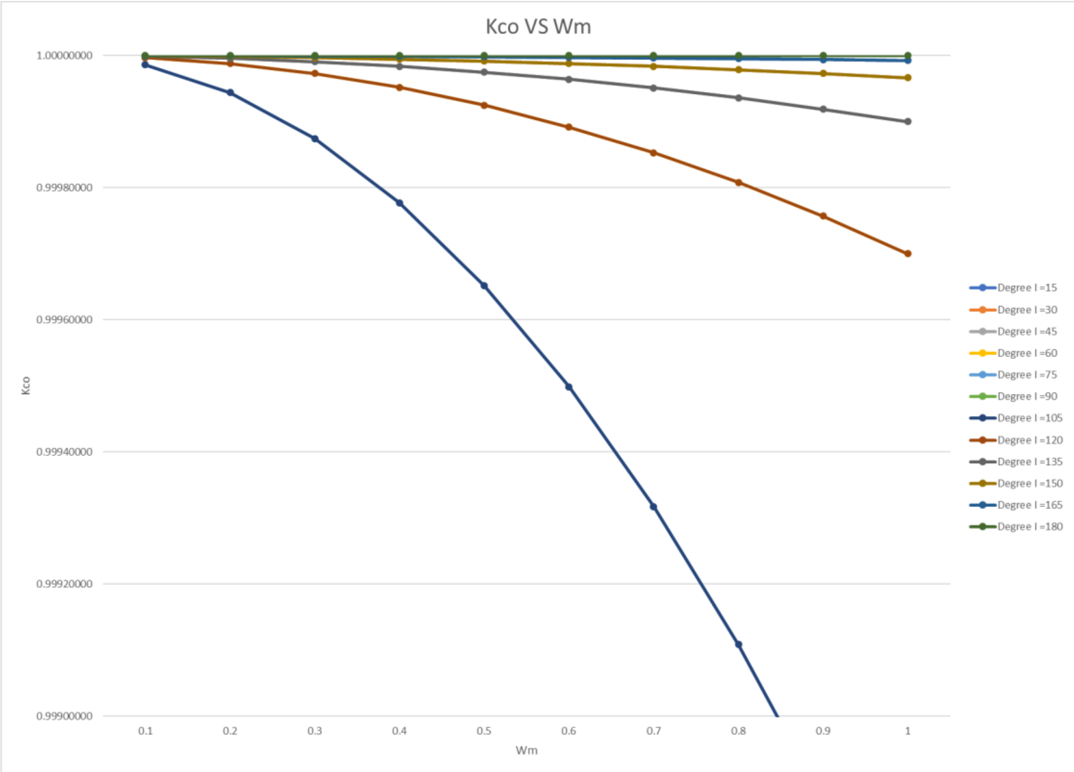


Fig. 4 K_{co} vs θ_i with 50 mm till 500 mm



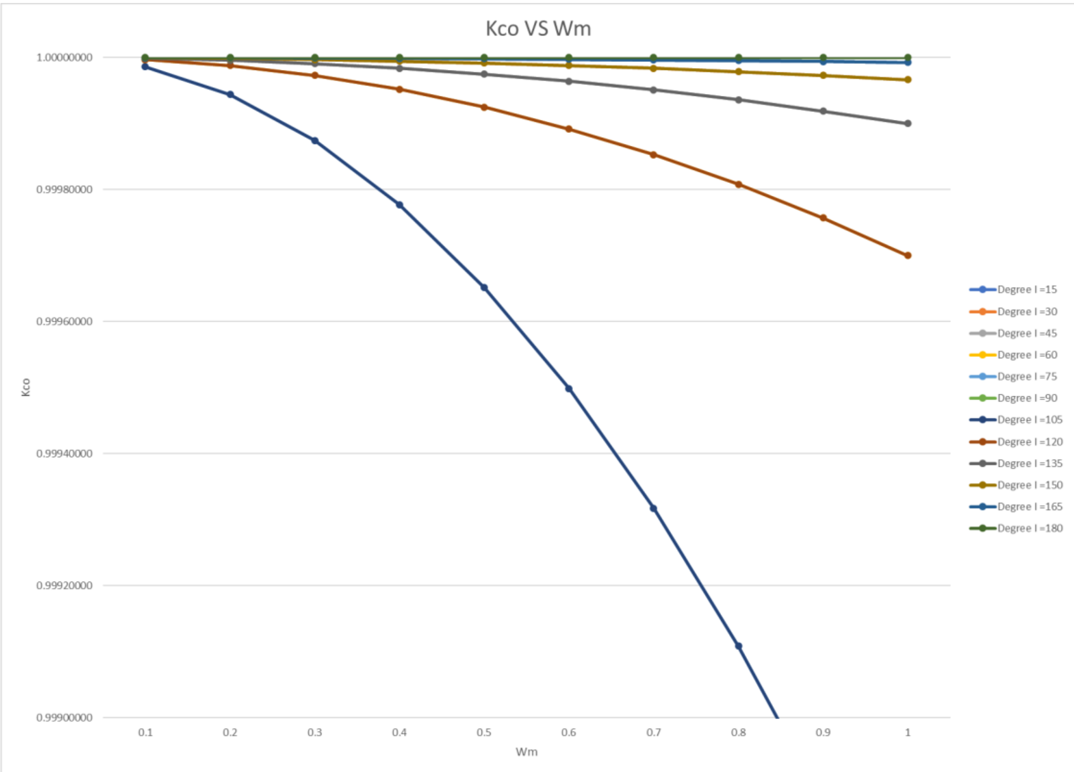


Fig. 5 K_{co} vs W_m with θ_i varies from 15° to 180°

Figure 3 shows the relationship between K_{co} and θ_i when W_m varies from 0.1 mm to 1.0 mm, f = 50 mm. It can be seen from the figure when θ_i increases from 0° towards 90°, K_{co} decreases correspondingly. On the other hand, when θ_i increases from 90° towards 180°, K_{co} inceases correspondingly

Figure 4 shows the relationship between K_{co} and θ_i when f varies from 50 mm to 500 mm and W_m = 1.0 mm, it can be seen from the figure that when θ_i varies from 0° to 90°, K_{co} decreases correspondingly. On the contrary, when θ_i varies from 90° to 180°, K_{co} gradually increases towards 1. It is worthwhile mentioning here that the smaller is the value of f, the greater is the range variation.

Figure 5 shows the relationship between K_{co} and W_m when θ_i varies from 15° to 180° and f = 50 mm. It can be seen from the figure that as W_m increases, K_{co} decreases. The effect is particularly pronounced when the θ_i increases.

Figure 6 shows the relationship between K_{co} and W_m when f as 50 mm to 500 mm and θ_i = 60°. It can be seen from the figure that as W_m increases, K_{co} decreases correspondimgly. The changes are more pronounced when the f is smaller.

Equation (2) quantifies the relative change in polarization state due to system interactions, which is critical for tuning system parameters to minimize unwanted polarization changes and optimize performance. The metric $C_{x\text{-}pol}$ describes the proportion of cross-polarization amplitude relative to the co-polarized beam. The larger the value, the greater the relative impact of cross-polarization. This is an intuitive metric for evaluating the magnitude of the impact of cross-polarization because it is directly related to the magnitude of the change in polarization state.

Figure 7 shows the cross-polarization relative amplitude $C_{x\text{-}pol}$ vs the angle of incidence θ_i when $Z = W_m/f$ varies from 0.1 to 1. It can be seen from the figure that the cross-polarization reaches its maximum value at some specific angles. An increase in the W_m/f ratio seems to result in a higher peak cross-polarisation. The peak of the cross-polarisation occurs at θ_i = 90°, after which it decreases sharply with increasing angle. When θ_i approaches 0 or 180°, $C_{x\text{-}pol}$ approaches zero, indicating that the effect of cross-polarisation is small at these angles. It is worthwhile noting that $C_{x\text{-}pol}$ can be kept at a low magnitude as the ratio W_m/f reduces.

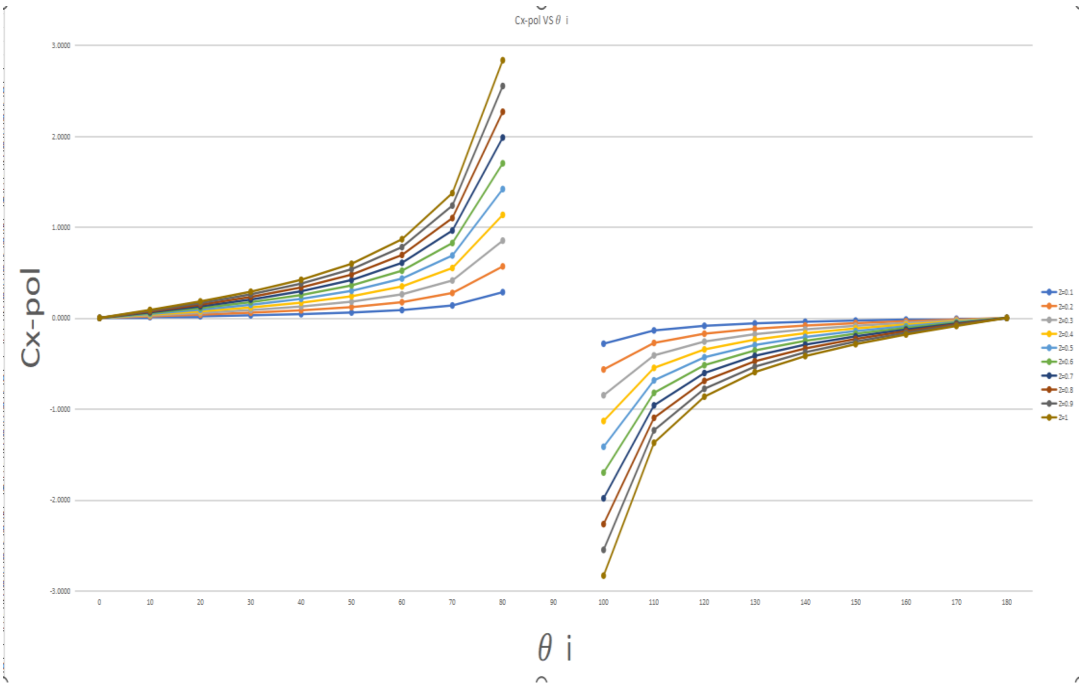


Fig. 7 Cx-pol vs θi with W_m/f varies from 0.1 to 1

In a nutshell, different combinations of beam radius W_m and focal length f values lead to significant changes in the curves. For most parameter combinations, there is a significant minimum in K_{co} as θ_i approaches 90°, indicating a peak in cross-polarization. Different combinations of W_m and f values lead to significant changes in the curves. For most parameter combinations, a significant minimum in K_{co} occurs as θ_i approaches 90°, indicating a peak in cross-polarization. At angles near 0° and 180°, the K_{co} values are the closest to 1, indicating that cross-polarization is minimized at these angles. These angles are the directions where the incident polarization state is least affected by the system. Configurations with larger focal lengths or smaller W_m values tend to show smaller K_{co} depths, indicating that these settings may result in lower cross-polarization. These angles are the directions in which the incident polarization state is least affected by the system. Configurations with larger focal lengths or smaller W_m values tend to show smaller K_{co} depths, indicating that these settings may result in lower cross-polarization. At angles near 0^o and 180^o, K_{co} values are the closest to 1, indicating that cross-polarization is minimized at these angles. These angles are the directions where the incident polarization state is least affected by the system. Configurations with larger focal lengths or smaller W_m values tend to show smaller K_{co} depths, indicating that these settings may result in lower cross-polarization. These angles are the directions in which the incident polarization state is the least affected by the system. Configurations with larger focal lengths or smaller W_m values tend to show smaller K_{co} depths, indicating that these settings may result in lower cross-polarization. In order to minimize the effect of cross-polarization, a larger focal length f and a smaller W_m value can be chosen, and in particular, when designing an optical system, care should be taken to choose a suitable range of θ_i in order to avoid peaks of cross-polarization close to 90^o. Recommendations are also made to prioritize the effects of these parameters on cross-polarization when designing optical or radio wave systems, especially in critical applications such as avoiding the introduction of additional noise or distortion in signal transmission and reception.

IV. CONCLUSION

In this paper, the relationship and significance represented by the influence of angle of incidence as well as other variables on cross-polarization is investigated. It was determined that the angle of incidence is a key factor affecting cross polarization, and image analysis was used to find specific patterns of change to the point where it can help optical system equipment optimize setup data to reduce cross polarization effects and thus enhance electromagnetic signal transmission. The basic goal of this project has been accomplished. However, there are still shortcomings in the project, as more new formulas or factors affecting cross-polarization have not yet been discovered, the number of arrays in the data attempt is still insufficient, and the images need to be further optimized to be more convincing.

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