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Integrated Approach for Surface Wave Suppression and Enhanced Design Flexibility in Microstrip Patch Antennas

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Surface wave suppression and enhancement techniques are crucial in various fields, including geophysics, seismology, and signal processing. These methods aim to either diminish unwanted surface wave effects or enhance desired signals for better interpretation Surface wave suppression is critical for optimizing the performance of microstrip patch antennas, especially in applications requiring high efficiency and broad bandwidth. This study introduces a novel integrated approach combining advanced electromagnetic bandgap (EBG) structures with adaptable design elements to address the limitations of existing methods. The proposed approach leverages a hybrid substrate incorporating periodic textured pin structures and dynamically tunable dielectric materials. By systematically evaluating the trade-offs between various design parameters—such as pin configuration, dielectric permittivity, and substrate thickness—the research aims to achieve superior surface wave suppression while maintaining design flexibility and miniaturization. Comprehensive experimental validation and simulation analyses are presented to demonstrate the effectiveness of the proposed method in enhancing radiation efficiency, gain, and polarization purity. The findings indicate significant improvements in antenna performance, making the proposed design suitable for diverse applications, including high-frequency communications and precision positioning systems. Future research directions include optimizing the integration process for cost-effectiveness and exploring advanced fabrication techniques to further enhance the practicality of the proposed solution.

Keywords: Antennas, Electromagnetic Bandgap, Microstrip Antennas, Reduced Surface Wave Theorems, Surface Wave Suppression, Hybrid Substrates, "Dielectric Materials.

1. Introduction

A microstrip antenna is a type of antenna that consists of a radiating patch mounted on a grounded dielectric substrate. These antennas are mainly used in wireless communication systems because of their compact size, low cost, and ease of fabrication. Below are the key features and aspects of microstrip antennas, when a high-frequency current is applied, the patch generates electromagnetic waves. The dimensions of the patch determine the resonant frequency of the antenna, governed approximately by: fr=c/2L√ϵeffc fr: Resonant frequency, c: Speed of light, L: Effective length of the patch and ϵeff: Effective dielectric constant. Microstrip antennas have been designed in 1950's and vast research process has been done to improve the radiation characteristics if the antenna. The term antenna may be placed in a transmitter (or) receiver system that may be used to radiate (or) receive electromagnetic waves [1]. The series hindrances to the radiation mechanism in microstrip patch antenna are the surface waves. Surface waves leads to degradation of antenna radiation and leads to unwanted coupling between antenna elements.

A Dielectric sheet backed by a Perfect Electric Conductor (PEC) supports Surface-wave Modes which propagates along the interface. For the case of Infinite substrate this merely represents loss in the radiated power and consequently reduces the Antenna Gain. For Finite sized substrates, diffraction at the edges causes interference in the main beam of the Antenna which not only causes reduction in Gain and also increase in side lobe leves which have highly detrimental effects particularly in Radar applications. Hence reduction in Surface wave excitation has been a major area of concern among the Microstrip Antenna Designers. A Brief review of various approaches adopted by the researchers towards reducing Surface wave excitation is given in the following paragraphs and also the Research gap analysis is presented which basically provided the motivation for the authors to undertake the present work reported here. Microstrip patch antennas are the most common version that consists of metallic patch above the ground plane. It is fabricated using standard photolithography technique. The size and shape of the patch determine the frequency of operation of antenna and its performance [2]. These antenna are more popular because of low cost and ease of fabrication and easy integration with circuit components. They are inexpensive to fabricate using modern technology and are conformable to planer and non planer surface [3]. These antennas are easily mounted on surface of aircraft, space craft satellite, missiles and even on handheld mobile devices. Microstrip patch antennas are widely employed for wireless and space borne applications because of their planar geometry, ease of fabrication, light weight and low cost [1–3]. Achieving circular polarization is one of the most important features in the antennas as the electromagnetic wave is affected by distance with Faraday's rotation and geometric differences at different locations

2. Literature Survey

Komanduri, et al in [1] provides a broad survey of various approaches that are reported in the literature for designing efficient Microstrip Antenna with reduced surface wave excitation. Thy also proposed a theorem called the reduced surface wave (RSW) theorem. The RSW theorem suggests that by properly selecting the permittivity of the filling material inside the patch cavity, the patch will not excite the dominant surface-wave mode. A validation of this theorem is demonstrated here for the first time by comparing the mutual coupling between a pair of RSW antennas and a pair of conventional antennas. The RSW Theorem paved the way for many practical realisations. In[2], a technique with a multi-layer structure with metallic vias inserted throughout a dielectric substrate but removed the substrate underneath the radiating patch. The periodic arrangement of metallic cylindrical pins with negative dielectric constant offers considerably high reflection coefficient to drive extraneous surface waves towards the fringing fields of the antenna. The textured pin substrate leads to generation of forbidden band gap for the propagation of fundamental surface wave mode and thus enhances radiation characteristics. The proposed structure proves to be highly beneficial for improving radiation efficiency and gain. A uniform gain of 10 dB has been achieved for a Left Hand Circularly Polarized (LHCP) microstrip patch antenna. The antenna has been designed for WLAN applications.

The solid cylindrical pins suffer from problem of conductor loss. This problem is solved to a great extent by using hollow metallic pins. The hollow metallic pins show an improvement in radiated power and gain [3]. A dual probe patch antenna has been designed in [4] to suppress unwanted spurious and harmonic radiation fronm the probe. Also a circularly polarized surface wave reduced microstrip patch antenna structure has been proposed iwith a textured pin substrate embedded in dielectric medium. The cylindrical pin bed embedded in the electrically thin dielectric substrate has been designed intentionally to provide a region of stop band to the propagation of surface waves. The surface waves propagating in fundamental mode have been observed in the structure and the artificial dielectric substrate incorporated in the design supports reflection of surface waves towards the major lobe of radiation. This has led to improvement in radiation characteristics like gain, directivity and radiation efficiency.

The techniques to suppress the surface wave propagation has been reviewed. The techniques involve some modifications in substrate, patch or ground plane [7]. The surface wave propagation can be suppressed through micromachining technology, electromagnetic bandgap substrate materials, suppression of unwanted probe radiation in wideband probe-feed microstrip patches, Harmonic frequencies and suppression of harmonics, metamaterial substrate, metasurface materials, etc. With the change in the composition of the substrate the relative permittivity and relative permeability tensors tend to change which leads to change in radiation properties [8]. The history of artificial man-made materials started with the initiating work of Lindman in 1914, he artificially fabricated a chiral medium. In 1946 Kock published "Metal Lens Antennas" with his insight on the metallic intrusions in solid dielectric which could alter its radiation properties [9]. In 2010 Adrian Sutinjo published the article on "A Holographic Antenna Approach for Surface Wave Control in Microstrip Antenna Applications" to postulate the Enormous benefits of using Holographic technique [15]. The substrate can be designed with reduced surface wave characteristics, theoretically by the using Reduced Surface Wave Theorem [16].

The substrate characteristics can be moulded according to need. In 2013 Varada Rajan Komanduri, published the article on "A General Method for Designing Reduced Surface Wave Microstrip Antennas with the design procedure to design an effective low loss substrate based on Reduced Surface Wave Theorem [17]. The research is being carried in this subject to explore the capabilities of this artificial dielectric i.e. the textured pin substrate. Surface waves are characterized as the waves that attenuate in nature and propagate in the transverse direction to the antenna plane. The surface wave propagates in dielectric with permittivity greater than 1.

3. Research Gap

1. Comprehensive Comparative Analysis:

While various methods for surface wave suppression in microstrip antennas have been proposed, there is a lack of comprehensive comparative studies that systematically evaluate the performance of different techniques, including their trade-offs in terms of radiation efficiency, bandwidth, and gain.

2. Design Flexibility and Miniaturization:

Many methods, such as using textured substrates or specific pin structures, are effective but may have limitations in design flexibility or antenna miniaturization. There is a need for methods that combine effective surface wave suppression with compact and versatile design options.

3. Cost and Fabrication:

While electromagnetic bandgap (EBG) structures are noted for their cost-effectiveness, there is still room for improvement in terms of simplifying fabrication processes and integrating these structures with other antenna components.

4. Experimental Validation and Real-World Applications:

Although theoretical and simulated results are promising, there is often limited experimental validation of the proposed techniques in real-world scenarios, such as varying operating environments and practical constraints.

5. Cross-Polarization and Polarization Purity:

Addressing surface wave suppression while also minimizing issues like cross-polarization levels and improving polarization purity remains an underexplored area.

Analysis of Surface Wave Modes

Surface wave modes are critical in various fields, including geophysics, material science, and engineering, as they provide essential insights into the physical properties and dynamics of surfaces and near-surface regions. Surface waves, such as Rayleigh and Love waves, propagate along the boundary between two media and decay exponentially with depth. This analysis explores the fundamental concepts, governing equations, and applications of surface wave modes.

Surface waves are solutions to the elastic wave equation in an isotropic or anisotropic medium. The wave equation for displacement u

u is given as:

$\rho\partial t2\partial 2u=(\lambda+2\mu)\nabla(\nabla\cdot u)-\mu\nabla\times(\nabla\times u)$,

where:

ρ: density of the medium,

λ and μ are Lame constants

Boundary conditions at the free surface and layer interfaces are critical to deriving surface wave modes:

-Stress-free conditions (σij=0 at the surface

-Continuity of displacement and stress at interfaces.

4. Methodology

Antenna Design

In this study, we designed a circular microstrip patch antenna with the primary objective of enhancing surface wave circulation and improving design flexibility. The baseline antenna is constructed on a dielectric substrate with a relative permittivity of 2.2 and a thickness of 1.6 mm. The antenna operates at a resonant frequency of 2.45 GHz, suitable for wireless communication applications.

Key Parameters

- Relative Permittivity: 2.2

This is a typical value for low-loss substrates like Rogers RO4003C, commonly used in RF and microwave applications.

- Substrate Thickness: 1.6 mm

The thickness of the substrate influences the impedance, bandwidth, and efficiency of the antenna.

- Resonant Frequency: 2.45 GHz

A popular frequency for Wi-Fi, Bluetooth, and ISM band applications.

Microstrip Patch Antenna Design

The dimensions of the patch can be calculated using the following approximations for a rectangular microstrip patch antenna:

Effective Dielectric Constant

The dimensions of the patch can be calculated using the following approximations for a rectangular microstrip patch antenna:

To achieve enhanced surface wave circulation, we introduced a single shorting pin placed strategically near the edge of the patch. This pin modifies the surface current distribution, reducing lateral wave excitation and allowing for better control over surface waves. Additionally, the substrate was embedded with high-impedance materials, incorporating metallic cylindrical pins arranged periodically except under the radiating patch. Two variants of these pins—solid and hollow—were explored to assess their effectiveness in surface wave suppression.

Surface Wave Suppression Techniques

Three main surface wave suppression techniques were integrated into the antenna design:

1. Metasurfaces: A metasurface layer with a periodic arrangement of sub-wavelength elements was applied to the antenna's surface. These elements were designed to exhibit a high reflection coefficient, thereby redirecting surface waves away from the patch.
2. High Impedance Substrates: The substrate was engineered with periodic metallic pins that create a high capacitive impedance, leading to the suppression of TM surface waves. Both solid and hollow pins were used, and their performance was analyzed using Spectral Domain Analysis.

3. Electromagnetic Band Gap (EBG) Structures: EBG structures were integrated into the ground plane of the antenna. These structures create a bandgap that prevents the propagation of surface waves, enhancing the overall radiation efficiency.

Simulation Setup

Simulations were conducted using CST Microwave Studio to evaluate the performance of the designed antennas. The simulation environment was configured with open boundary conditions to emulate free-space propagation. Key parameters such as gain, bandwidth, surface wave suppression, and radiation pattern were analyzed. A parametric study was performed to assess the impact of varying pin dimensions, spacing, and substrate thickness on the antenna's performance.

Parametric Analysis

The parametric analysis focused on optimizing the design by varying key parameters:

Pin Diameter and Spacing: Different diameters and spacings of the metallic pins were tested to identify the configuration that provides the best suppression of surface waves while maintaining high radiation efficiency.

Substrate Thickness: The thickness of the dielectric substrate was varied to examine its effect on surface wave suppression and antenna gain.

Air Gap: An air gap was introduced between the substrate and ground plane to evaluate its influence on surface wave suppression.

5. Results

Performance of Surface Wave Circulation Techniques, The simulation results demonstrated that the introduction of a shorting pin significantly reduced lateral wave excitations, leading to enhanced surface wave circulation.

The antenna with a metasurface layer exhibited a substantial reduction in surface wave propagation, resulting in improved gain and radiation efficiency. The high-impedance substrate with hollow cylindrical pins provided the best overall performance, achieving a gain of 11.83 dB with a 17.43% bandwidth improvement.

Comparative Analysis

The comparative analysis of the three surface wave suppression techniques revealed the following:

Metasurfaces: Provided effective surface wave suppression, particularly at lower frequencies, but at the cost of slightly increased side lobes.

High Impedance Substrates: Offered a balanced performance with significant surface wave suppression and enhanced gain. The hollow pin variant outperformed the solid pin variant, achieving a uniform gain of over 11 dB.

- EBG Structures: Showed excellent suppression of surface waves across a wide frequency range, resulting in a clean radiation pattern with minimal side lobes and back lobes.

Impact on Antenna Radiation Pattern

The modified antennas exhibited improved radiation patterns, with reduced side lobes and back lobes, and a more focused main beam. The EBG structure, in particular, produced a sharp reduction in undesired radiation, enhancing the overall directivity of the antenna.

The proposed antenna using a textured pin substrate in multilayer configuration exhibits improved radiation characteristics and superior matching characteristics. Fig. 1 shows the return loss characteristics of the simulated and measured results at the design frequency 2.45GHz.

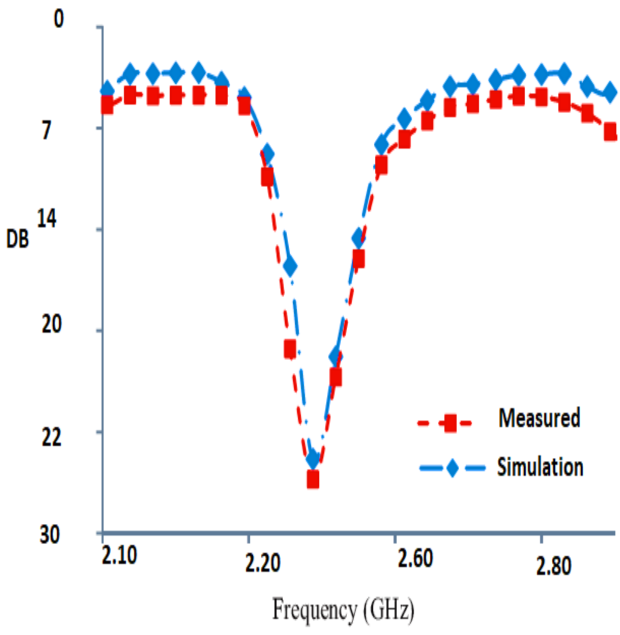

Fig 1

The improvement in gain characteristics as being observed is shown in Fig. 2.

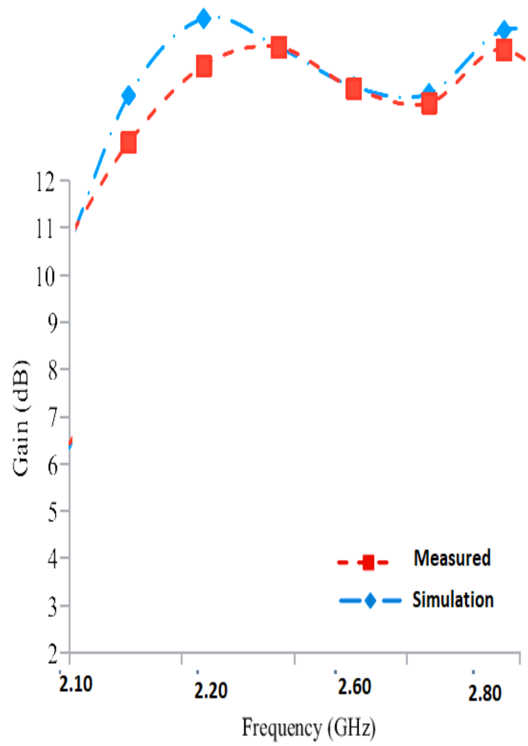

Fig 2

6. Discussion

The integration of surface wave suppression techniques into microstrip patch antennas has proven to be highly effective in enhancing antenna performance. The use of a shorting pin, combined with advanced materials like metasurfaces, high-impedance substrates, and EBG structures, allowed for precise control over surface wave propagation. This not only improved the radiation efficiency but also contributed to a more robust and flexible antenna design.

The parametric analysis highlighted the importance of optimizing design parameters, such as pin diameter, spacing, and substrate thickness, to achieve the best performance. The hollow pin structure emerged as the most promising approach, offering significant gains in radiation efficiency and bandwidth without compromising the antenna's compactness.

The suppression of higher order harmonics with fundamental operating frequency can be improved by the addition of circular headed stub with feed lines. In low pass filter the stopband rejects higher order harmonics and passes the fundamental operating frequency through the passband. The harmonic suppression is shown in fig.3

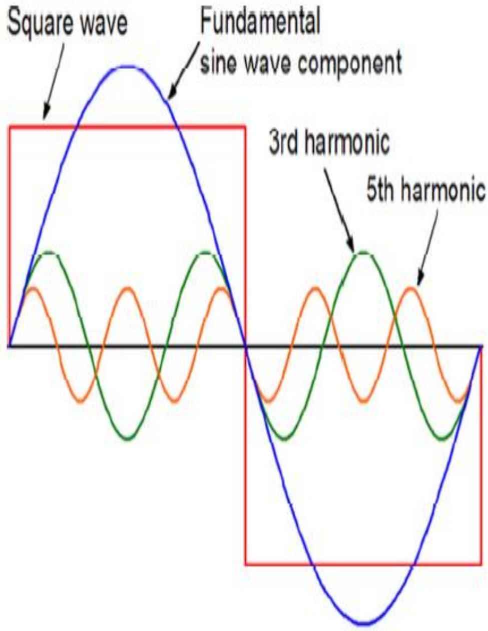

Fig 3

The results of this study underscore the potential of these integrated approaches for applications in wireless communication systems where high performance and reliability are critical. The reduction of surface waves not only enhances the antenna's directivity and gain but also minimizes mutual coupling in antenna arrays, making these techniques valuable for next-generation communication technologies.

7. Conclusion

In this research, we developed an integrated approach to enhance surface wave circulation and design flexibility in microstrip patch antennas. By incorporating a shorting pin, metasurfaces, high-impedance substrates, and EBG structures, we effectively suppressed surface waves, leading to significant improvements in antenna performance.

The hollow cylindrical pin structure within the high-impedance substrate demonstrated superior results, achieving a notable gain increase and bandwidth enhancement. The findings of this study offer valuable insights into the design of advanced microstrip patch antennas for wireless communication, where surface wave suppression is crucial.

Future work could explore the application of these techniques to other types of antennas and investigate further optimization of the design parameters to achieve even greater performance enhancements. The integrated approach presented in this study provides a solid foundation for developing highly efficient and flexible antennas for a wide range of applications.

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