

edited by  
Douglas H. Werner



# Broadband Metamaterials in Electromagnetics

*Technology and Applications*







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# Preface

Metamaterials are artificial electromagnetic or optical media whose bulk (macroscopic) properties are controlled by engineering their structure on the subwavelength (microscopic) scale. The rapid development of technology based on metamaterials, coupled with the recent introduction of the transformation optics technique, provides an unprecedented ability for device designers to manipulate and control the behavior of electromagnetic wave phenomena. Many of the early metamaterial designs, such as negative index materials and electromagnetic bandgap surfaces, were limited to operation only over a very narrow bandwidth. However, recent groundbreaking work reported by several international research groups on the development of broadband metamaterials has opened up the doors to an exciting frontier in the creation of new devices for applications ranging from radio frequencies to visible wavelengths.

This book contains a collection of eight chapters, which cover recent cutting-edge contributions to the theoretical, numerical, and experimental aspects of broadband metamaterials. Chapter 1 provides an overview of recent advances in utilizing custom designed anisotropic metamaterials to enable broadband performance in microwave antennas. Several application examples are presented where anisotropic metamaterials with engineered dispersion and negligible loss have been employed to extend the impedance bandwidth and/or enhance the gain of antennas. These include the design of an ultrathin lightweight anisotropic metamaterial coating for extending the bandwidth of conventional monopole antennas, single-polarization and dual-polarization anisotropic zero-index metamaterial lenses for achieving high unidirectional radiation, transformation electromagnetics lenses with low-index properties for generating multiple highly directive beams along with extended impedance bandwidth, and a concept for realizing tunable versions of the low-index lenses capable of reconfigurable beam scanning.

One of the earliest documented examples of a broadband low-loss dispersion engineered metamaterials is highlighted in Chapter

2. This work represented a pivotal point in metamaterials' development by demonstrating the first practical broadband negligible-loss device (a horn antenna) to benefit from the application of metamaterials technology. By properly engineering the dispersive characteristics of a metamaterial liner inside a horn antenna, it is shown that the bandwidth of a conventional narrowband horn can be extended to operate over an octave or more with negligible intrinsic losses and low cross-polarization. Examples of broadband horn antenna prototypes that were fabricated and measured are presented for the C-band and  $K_u$ -band with wire-grid and printed circuit board type metamaterial liners, respectively. For maximum performance, it is shown that inhomogeneous metamaterials can be applied as horn liners to support broadband balanced hybrid modes and create polarization-independent patterns suitable for dual-polarized communication systems such as those commonly employed in satellite applications.

Chapter 3 provides, for the first time, an understanding of how exotic propagation phenomena can be explained and controlled using dispersion engineering. More importantly, these novel propagation modes are generated using a set of coupled transmission lines that can be printed on simple substrates. By controlling the propagation constant on each line, as well as their mutual capacitance and inductance, it is shown that these transmission line systems can be designed to support various exotic modes. These modes can be subsequently utilized to (i) improve the electronic efficiency of traveling wave tubes, (ii) miniaturize antennas, reaching their optimal limits, (iii) increase antenna directivity, and (iv) control antenna bandwidth. Several practical examples of this transformative design methodology are presented and discussed.

Chapter 4 presents a powerful and highly efficient synthesis technique for the custom design of multiband and broadband electromagnetic bandgap (EBG) devices, which are based on the well-known Sievenpiper surfaces. The synthesis approach optimizes the non-uniform capacitive loading of a periodic array of fixed metallic mushroom-type structures in order to meet a desired design objective. In this way, both the inhomogeneous and anisotropic properties of the metasurfaces can be engineered simultaneously. The approach exploits the fact that EBGs loaded with lumped capacitors can be conveniently represented as multi-port networks whose re-

sponse is fully characterized by their  $S$ -matrix. Consequently, their analysis can be performed via simple and efficient circuit-based calculations rather than through computationally expensive full-wave simulations. It is shown that non-uniform capacitively loaded EBGs exhibit, in principle, wider bandgaps compared to those of the same EBG with uniform capacitive loads. Finally, it is demonstrated that this circuit-based analysis can be extended for the design of mushroom-type absorbers loaded with lumped tuning capacitors and resistors.

Chapter 5 establishes the conceptual foundations for performing ultrafast real-time spectrum analysis through the use of broadband metamaterials. The principle is based on the radio-analog signal processing (R-ASP) paradigm, which makes use of temporal and spatial phasers to discriminate the spectral components of a broadband signal in time and space, without resorting to digital computations. Three different systems for ultrafast real-time spectrum analysis applications are considered: (i) a 1D real-time spectrum analyzer (RTSA) based on a composite right/left-handed (CRLH) transmission line system to decompose a broadband signal along one dimension of space, (ii) a spatio-temporal 2D RTSA combining temporal and spatial phasers to perform spectral decomposition in two dimensions of space to achieve higher frequency resolution in the RTSA system, and (iii) a spatial 2D RTSA using metasurface phasers to spectrally decompose an incident pulsed wavefront onto two dimensions of space. These three systems are particularly well suited for mm-wave and terahertz high-speed applications, where digital computation is not readily available.

Chapter 6 provides a comprehensive treatment of the newly emerging and important topic concerned with broadband lens designs enabled or inspired by the quasi-conformal transformation optics (qTO) technique. Example lens designs are presented for both radio frequency and optical applications. The resulting lens designs are shown to possess desirable performance over a large field-of-view (FOV) and/or wide frequency range. First, the mathematics of transformation optics and the numerical algorithm qTO are described. Next, a series of broadband qTO-derived inhomogeneous metamaterial lenses are presented, which were created by transforming the geometry of classical designs, including the Luneburg and Fresnel lenses. Then, qTO is employed to transform

wavefronts and design a broadband gradient-index (GRIN) multi-beam lens antenna. A systematic approach is introduced next for using qTO to design anti-reflective coatings. In addition, the wavefront matching (WFM) technique is discussed, which is a powerful design tool that can be used to correct for dispersion in complex multi-element optical lens systems. The final section looks at the effects of material dispersion on the performance of GRIN lenses, while a set of classical and qTO-inspired corrections are presented.

In Chapter 7, a distinct class of structures known as twisted metamaterials is explored. It is demonstrated that wave propagation through these metamaterials exhibits new phenomena, which are not available in conventional periodic metamaterials, such as a broadband chiral response. A detailed examination of the electromagnetic wave propagation in these unique metamaterial structures is provided. A generalized Floquet analysis is developed and applied to obtain rigorous modal solutions to lossless as well as lossy twisted metamaterials. The chapter concludes with a discussion of the wave polarization properties and potential applications of twisted metamaterials for broadband polarizer designs.

Chapter 8 summarizes recent breakthroughs in the development as well as applications of broadband optical metamaterials and metasurfaces. Dispersion engineering is introduced as a powerful design methodology for exploiting the resonant properties of metamaterials over broad wavelength ranges in order to enhance the performance of existing or realize new optical devices. Several examples are presented, including a demonstration of how metamaterial loss can be exploited for broadband absorption in the infrared regime. A robust genetic algorithm (GA) synthesis technique is employed to design super-octave and multi-octave metamaterial absorbers using only a single patterned metallic screen. Broadband optical metasurfaces that can control the phase and polarization of a reflected wave are also considered. Optical metasurface designs are presented along with measurement results that demonstrate broadband and wide-angle quarter-wave and half-wave plate functionalities. Another type of metasurface based on nanoantenna arrays that can artificially induce a phase gradient in the cross-polarized reflected or transmitted wave at an interface and, therefore, steer and focus light is also presented. Together, these

nanostructured metamaterial and metasurface examples illustrate the potential for realizing practical optical devices with unique functionalities over broad bandwidths.

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