Contributed Papers

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P19 2 Total and negative refraction in real crystals for ballistic electrons and light YONG ZHANG, BRIAN FLUEGEL, ANGELO MASCARENHAS, *National Renewable Energy Laboratory* It is found that there exists a category of material interfaces, readily available, that not only can provide total refraction (i.e., zero reflection) but can also give rise to amphoteric refraction (i.e., both positive and negative refraction) for electromagnetic waves in any frequency domain as well as for ballistic electron waves. These two unusual phenomena are demonstrated experimentally with the propagation of light through such an interface. Y. Zhang, B. Fluegel, and A. Mascarenhas, Phys. Rev. Lett. 91, 157404 (2003) The work was supported by the U.S. Department of Energy, Office of Sciences, Basic Energy Sciences under contract No. DE-AC36-99GO10337

12:03

P19 3 Negative Refractive Bi-Crystal with Broken Symmetry Leading to Unusual Fields in Guided Wave Heterostructures CLIFFORD KROWNE, *Naval Research Laboratory* A recent finding has shown that a unixial bi-crystal shows negative refraction (NR) [1], a property in common with recent left-handed metamaterials examined for physics of focusing behavior and of field distributions [2], and field contouring effects in electronic structures [3]. This is a very interesting property related to energy wave front motion and has an analog in electron ballistic motion in a semiconductor heterostructure too. The property which yields NR, breaks field symmetry, and allows asymmetric distributions of electromagnetic fields in the cross-section in which heterostructure layering occurs when propagation is normal to this cross-section in a longitudinal direction. What is all the more remarkable is that individual heterostructure layers are not field symmetry breaking and do not lead to asymmetric field distributions. In fact when a single crystal is inserted in a guiding structure, nothing special happens. When heterostructure layering is constructive, successive layers could enhance the effect. We demonstrate here for the first time, using a model stripline structure to guide the wave, that a bi-crystal will indeed produce asymmetric rf electric and magnetic distributions. Calculations were done with an ab initio approach using an anisotropic Greens function which allows the physical properties of the uniaxial crystals to be treated via their tensors. The results have important implications for microwave devices which rely on asymmetric field distributions. One could envision wide application in monolithic integrated circuits in terms of devices utilizing both microwave and millimeter transmission as well as optical transmission using dielectric waveguiding structures. [1] Y. Zhang, B. Fluegel and A. Mascarenhas, Phys. Rev. Lett. 91, 157404 (Oct. 2003). [2] C. M. Krowne, Phys. Rev. Lett. 92, to be publ. (2004). [3] C. M. Krowne, IEEE Trans. Microwave Theory & Tech. 51, (Dec. 2003).

12:15

P19 4 Nonlinear waves in left-handed metamaterials and waveguides ILYA SHADRIVOV, ANDREY SUKHORUKOV, YURI KIVSHAR, *Nonlinear Physics Group and CUDOS, Australian National University* ALEXANDER ZHAROV, *Institute for Physics of Microstructures* NONLINEAR PHYSICS GROUP, RESEARCH SCHOOL OF PHYSICAL SCIENCES, AUSTRALIAN NATIONAL UNIVERSITY TEAM We study nonlinear waves in microstructured left-handed metamaterials. First, we consider a two-dimensional periodic structure of wires and split-ring resonators embedded into a nonlinear dielectric, and analyze the effective nonlinear properties of such structures. We demonstrate that the hysteresis-type dependence of the magnetic permeability on the field intensity allows changing the material properties from left- to right-handed and back. Second, we study both linear and nonlinear guided waves in slab waveguides created by right- and left-handed media, and describe the intensity-dependent properties of nonlinear surface waves in three different types of waveguide structures. Finally, we demonstrate that nonlinear left-handed media can support novel types of solitary waves with many unusual properties.

12:27

P19 5 Effective medium theory of left-handed materials TH. KOSCHNY, M. KAFESAKI, R. PENCIU, N. KATSARAKIS, E. N. ECONOMOU, *IESL-FORTH, Heraklion, Crete, Greece* C. M. SOUKOULIS, *Ames Lab. and Iowa State Univ.* We investigate the transmission properties of one-dimensional left-handed materials (LHM) and related meta-materials of the split-ring resonator (SRR) and continuous wire type, both theoretically and experimentally. Theoretically, we use the transfer matrix method, to calculate the complex transmission and reflection amplitudes for arbitrary structures inside the unit cell. Moreover, we apply an inversion procedure to the obtained scattering data, to retrieve the effective permittivity and permeability as a function of frequency. This allows us to show the negative index of refraction $n(\omega) < 0$ together with simultaneously $\epsilon_{eff}(\omega) < 0$ and $\mu_{eff}(\omega) < 0$ nside the left-handed bandpass for the one-dimensional materials and normal incidence. We show that the explanation for the LHM behavior is more complicated than just the combination of the negative $\mu_{eff}(\omega)$ provided by the SRRs with the negative $\epsilon_{eff}(\omega)$ from the wires, and *we propose a simple analytic model for this behavior.* We find that the SRRs have a strong electric response, equivalent to that of cut-wires, which dominates the behavior of LHM. It also explains the occasional appearance of right-handed instead of the expected left-handed bandpasses in LHM around the SRR resonance.

12:39

P19 6 Delay time investigation of EM waves through homogeneous and photonic crystals left-handed materials R. MOUSSA, S. FOTEINOPOULOU, C. M. SOUKOULIS, *Ames Laboratory - USDOE and Physics Department, Iowa State University, Ames, Iowa, 50011, USA* Results for the delay time that the EM wave needs before reaching its final direction through both photonic crystals and homogeneous media are presented. Different cases and different incoming wave angles will be discussed. It is found that the diffracted beam is trapped at the interface and this delay time is twice as large for the negative refractive index photonic crystal, compared with the positive index case. The role of dispersion was also studied. For the homogeneous medium, the excitation of surfaces waves at the interface of the right-handed and left-handed medium might be responsible for the time delay. A comparison between left-handed behavior in photonic crystals and homogeneous media will be also reported.

12:51

P19 7 Transmission Line Metamaterials with Effective Negative Refractive Index and Negative Group Delay SUZANNE J. ERICKSON, OMAR F. SIDDIQUI, GEORGE V. ELEFTHERIADES, MOHAMMAD MOJAHEDI, *University of Toronto, Edward S. Rogers Sr. Dept. of Electrical and Computer Engineering*

WEDNESDAY MIDDAY \ P19

We have simulated and constructed a 1-D metamaterial, composed of a periodically-loaded transmission line that exhibits both negative and positive group delays within a band of effective negative refractive index. By tuning the signal frequency, we are able to achieve both negative and positive phase and group delays, and thereby we can control the phase and group refractive indices of electromagnetic pulses traveling in the effective medium. The calculated and measured S-parameters of the metamaterial in the frequency domain will be presented, showing the regions of negative and positive phase delay, and negative and positive group delay. The time-domain behaviour will be demonstrated with Gaussian pulse propagation simulation and experimental results, where negative delays of up to -3.1 ns have been experimentally achieved with a 40-ns-wide pulse. Further novel configurations of transmission line metamaterials will also be discussed.

12:03

P19 8 Microwave pulse propagation measurements in left-handed materials EMILIANO DI GENNARO, PATANJALI V. PARIMI, PLARENTA VODO, WENTAO LU, SRINIVAS SRIDHAR, *Department of Physics, Northeastern University, 360 Huntington Avenue, Boston, MA 02115* Left handed electromagnetism is well established in media with negative permeability and permittivity and in photonic crystals [1]. In such media the negative refractive index is accompanied by large dispersion dn/dω, and consequently a very low group velocity is predicted for left-handed metamaterial (LHM). It is well known that an artificial material consisting of interleaved arrays of wires and split ring resonators in a certain microwave frequency range shows left handed behavior. We have carried out pulse measurements on LHM using a transition analyzer in order to measure the group velocity. Time delay measurements are performed in an X-band and parallel plate waveguide. Sending a 100ns width pulse with a carrier frequency ranging between 9 and 11 GHz, we analyze the signal delay due to the sample. The results suggest that the group velocity in the LHM is very low. Pulse delay measurements in photonic crystals are also discussed. Work supported by NSF & AFRL [1]. P. V. Parimi et al., submitted (2003).

SESSION P20: NOVEL ORDERED PHASES

Wednesday midday, 24 March 2004
512CG, Palais des Congres at 11:15
Eduardo Fradkin, University of Illinois at Urbana-Champaign, presiding

11:15

P20 1 A Class of P,T-Invariant Topological Phases of Interacting Electrons MICHAEL FREEDMAN, *Microsoft* CHETAN NAYAK, *UCLA* KIRILL SHTENGEL, *Microsoft* We describe a class of parity- and time-reversal-invariant topological states of matter which can arise in correlated electron systems in 2+1-dimensions. These states are characterized by particle-like excitations exhibiting exotic braiding statistics. P and T invariance are maintained by a 'doubling' of the low-energy degrees of freedom which occurs naturally without doubling the underlying microscopic degrees of freedom. The simplest examples have been the subject of considerable interest as proposed mechanisms for high-T_c superconductivity. One is the 'doubled' version (i.e. two opposite-chirality copies) of the U(1) chiral spin liquid. The second example corresponds to Z_2 gauge theory, which describes a scenario for spin-charge separation. Our main concern, with an eye towards applications to quantum computation, are richer models which support non-Abelian statistics. All of these models, richer or poorer, lie in a tightly-organized discrete family. The physical inference is that a material manifesting the Z_2 gauge theory or a doubled chiral spin liquid might be easily altered to one capable of universal quantum computation. These phases of matter have a field-theoretic description in terms of gauge theories which, in their infrared limits, are topological field theories. We motivate these gauge theories using a parton model or slave-fermion construction and show how they can be solved exactly. The structure of the resulting Hilbert spaces can be understood in purely combinatorial terms. The highly-constrained nature of this combinatorial construction, phrased in the language of the topology of curves on surfaces, lays the groundwork for a strategy for constructing microscopic lattice models which give rise to these phases.

11:27

P20 2 An extended Hubbard model with a possible non-Abelian topological phase KIRILL SHTENGEL, *Microsoft Research* MICHAEL FREEDMAN, *Microsoft Research* CHETAN NAYAK, *UCLA* We propose an extended Hubbard model on a $2D$ Kagomé lattice with an additional ring-exchange term. The particles can be either bosons or spinless fermions. At a special filling fraction of 1/6 the model is analysed in the lowest non-vanishing order of perturbation theory. Such "undoped" model is closely related to the Quantum Dimer Model. We show how to arrive at an exactly soluble point whose ground state manifold is the extensively degenerate "d-isotopy space," a necessary pre-condition for for a certain type of non-Abelian topological order. Near the special values, $d = 2\cos\pi/(k+2)$, this space is expected to collapse to a stable topological phase with anyonic excitations closely related to $SU(2)$ Chern-Simons theory at level k.

11:39

P20 3 Topological order and conformal quantum critical points in a quantum eight-vertex model* EDDY ARDONNE, *Department of Physics, University of Illinois at Urbana-Champaign* PAUL FENDLEY, *Department of Physics, University of Virginia, Charlottesville* EDUARDO FRADKIN, *Department of Physics, University of Illinois at Urbana-Champaign* We discuss the phase diagram of a quantum generalization of the classical eight-vertex model. The ground state of this model is related to the partition function of the classical eight-vertex model and has (spatial) conformal symmetry. The rich phase diagram of the model exhibits conventional ordered phases, with broken Z_2 symmetry and confined excitations. In addition, there is a quantum disordered phase, which supports deconfined excitations and is topological in nature. Several lines of fixed points, along which the critical exponents are varying continuously, separate these phases. At these conformal quantum critical points, the correlations are given by the correlation functions of the quantum Lifshitz model, a quantum relative of the Lifshitz model for three-dimensional anisotropic classical systems.

*Eddy Ardonne, Paul Fendley, Eduardo Fradkin, cond-mat/0311466