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PHOTONICS AND NANOSTRUCTURES
Fundamentals and Applications

Photonics and Nanostructures – Fundamentals and Applications 10 (2012) 83–101

www.elsevier.com/locate/photonics

Compact optical circulator based on a uniformly magnetized ring cavity

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Received 15 May 2011; accepted 18 July 2011
Available online 25 July 2011

Abstract

We propose a new class of compact integrated optical circulators providing a large isolation level while maintaining a straightforward technological feasibility. Their layout is based on a nonreciprocal radial Bragg cavity composed of concentric magneto-optical rings. The circulator ports are standard rib waveguides, butt-coupled to the cavity by cutting through its outer rings. The device is specifically designed for operation in a uniform external magnetic field. Using a coupled-mode description of the complete cavity/waveguide-port system, we explore the rich behaviour of cavity circulators in presence of varying levels of direct port-to-port coupling. We demonstrate numerically a strongly miniaturized two-dimensional cavity circulator, with a total footprint of less than $(10\lambda)^2$, achieving a 20-dB isolation level at telecom frequencies over a bandwidth of 130 GHz. The device is found to be very tolerant with respect to fabrication imperfections. We finish with an outlook on three-dimensional versions of the proposed nonreciprocal cavities.

Keywords: Magneto-optics; Integrated optics; Circulators; Resonant cavities; Fano resonances; Coupled-mode theory

1. Introduction

The need for an integrated and miniaturized version of an optical isolator, or more generally an optical circulator, is making itself increasingly felt. The drive towards ever higher degrees of all-optical on-chip integration is often hindered by the absence of an element that induces a one-way sense in the path of the signal in such an integrated circuit. Without it, long path interferences can lead to large changes somewhere in the circuit due to small amplitude oscillations at a remote point. Commercially available isolators are bulk free-space devices based on 45° nonreciprocal magneto-optical (MO) Faraday polarization rotators in combination with polarizers placed at their entrance and exit. The most commonly used MO materials are magnetic garnet oxides such as Ce-substituted $Ce_xY_{3-x}Fe_5O_{12}$ (Ce:YIG), combining optical transparency and strong MO properties at telecom frequencies. Realisation of an integrated isolator based on the Faraday-effect is very difficult because of the inevitable geometric birefringence of planar integrated waveguide circuits.

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doi:10.1016/j.photonics.2011.07.004

Nowadays, research efforts focus on integrated isolator concepts that do not depend on polarization conversion [1]. This can be achieved by properly orienting the magnetization in the MO material so that no coupling occurs between the quasi-TE and quasi-TM waveguide modes. Phase velocity and field profiles of the waveguide modes then become different for forward and backward propagation, while their polarization state is unchanged. This has been exploited in order to propose various concepts based on nonreciprocal interference [2,3], multimode imaging [4], microring and -disk resonators [5,6], etc. Nevertheless, experimental demonstration of garnet-based isolators suffers from the limited MO gyrotropy in the optical and near-infrared regime. This leads to high device lengths (typically of the order of 1 mm), which goes hand in hand with serious technological challenges, for instance to maintain magnetic uniformity. As a result, during the past decade the use of resonant photonic-crystal (PhC) layouts has attracted a lot of interest. Magnetophotonic crystals allow to artificially enhance the intrinsic strength of the basic MO effects [7,8]; in addition, removal of time-reversal symmetry in periodic structures leads to the appearance of novel phenomena, such as frozen light [9], photonic chiral edge states [10] and one-way band gaps [11,12]. Over the last few years, an increasing number of promising miniaturized isolator (and circulator) designs using PhC effects have been reported [13–16].

In this article, we will focus on a particular class of miniaturized integrated circulator designs based on the resonant enhancement of the light–MO-material interaction in a nonreciprocal cavity. Uniformly magnetized resonant ferrite cavities have been used for decades in microwave circulators [17]. However, optical circulators made by a simple geometric rescaling of existing microwave devices would have prohibitively low operation bandwidths. Indeed, at optical frequencies nonreciprocal effects are induced by the gyroelectric off-diagonal elements of the permittivity tensor, which are typically one or two orders of magnitude smaller than the analogous gyromagnetic off-diagonal elements of the permeability tensor in the microwave regime [18]. In 2005, Wang and Fan reported a solution for a cavity circulator operating at optical frequencies [13]. The proposed device is composed of a 2D PhC cavity etched in bismuth iron garnet (BIG)—a transparent magnetic oxide with record MO properties [19]. The cavity is evanescently coupled to three symmetrically placed PhC waveguides. It achieves an infinitely strong circulation at the resonant wavelength of the cavity and has a footprint of just a few square wavelengths. However, under uniform magnetization the spectral bandwidth of this circulator becomes negligibly small, reducing ultimately the applicability of the device. A reasonable bandwidth of the order of 50 GHz can only be achieved by imposing a very specific domain structure of antiparallel magnetic domains. Achieving and maintaining this magnetic domain structure within an area of a few μm^2 is unfeasible.

In order to remedy the unfeasibility of this concept we reported earlier an original design approach for a PhC cavity that provides simultaneously high circulation levels ($\geq$30 dB), good spectral bandwidth ($\sim$80 GHz), and operates in a uniformly magnetized MO material [14]. The new concept is based on an approximately axisymmetric arrangement of the holes making up the PhC cavity. In this work we propose to eliminate entirely the use of the PhC layout, forming instead a fully axisymmetric cavity composed of concentric MO rings and butt-coupling it to standard rib waveguides. The general geometry of the proposed new cavity circulator is shown in Fig. 1. If this device shows similar performance as the cavity circulators proposed in Refs. [13–15], its markedly simpler layout would make it far preferable over the existing circulator schemes. There are nevertheless important issues to be tackled. The circular Bragg grating formed by the concentric full and split rings can in theory provide sufficient confinement [20,21]. However, the quality

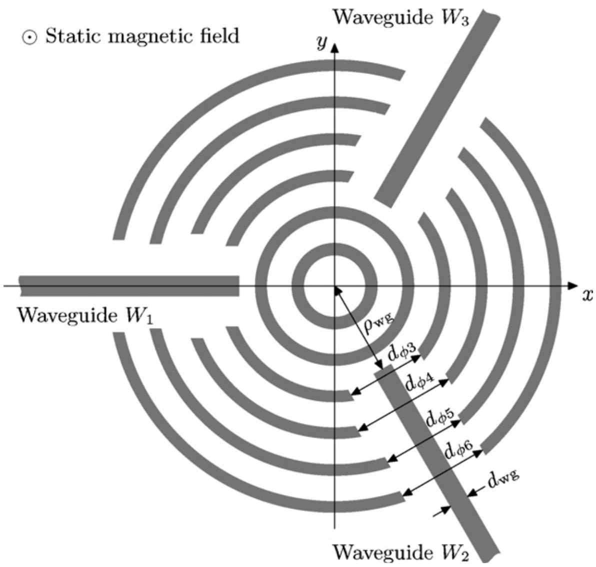

Fig. 1. Geometry of a circulator composed of a ring cavity butt-coupled to three rib-waveguides. A uniform magnetic field perpendicular to the *xy* plane causes nonreciprocal coupling of the even and odd degenerate *H*-polarized cavity modes. The number of split and full rings, n_s resp. n_f, the width of the slits in the split rings, $d_{\phi n}$, and the distance from the waveguide ends to the centre of the cavity, ρ_{wg}, are all design optimization parameters.