DEMONSTRATION OF MICROFIBER HYBRID MACH–ZEHNDER AND KNOT RESONATOR STRUCTURE

A. Sulaiman,[1] S. W. Harun,[1,2] F. Ahmad,[1,3] M. Z. Muhammad,[1] A. A. Jasim,[1] and H. Ahmad[2]
[1] Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia; Corresponding author: swharun@um.edu.my
[2] Photonics Research Center, Department of Physics, University of Malaya, 50603 Kuala Lumpur, Malaysia
[3] Department of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 54100 Kuala Lumpur, Malaysia

Received 21 April 2012

ABSTRACT: *We demonstrate a microfiber hybrid structure consisting of a microfiber knot resonator (MKR) and a microfiber Mach–Zehnder interferometer (MMZI) by micro-manipulating a microfiber. The microfiber used has a waist diameter of 1 μm and is fabricated using a flame brush technique. The hybrid structure generates dual resonances spectrum, which combines a characteristic resonant of MKR and MMZI. The MMZI resonant exhibits a much higher free spectral range (FSR) of 3.1 nm with the extinction ratio of 3 dB. The MKR resonant has a FSR of 0.24 nm and extinction ratio of 5 dB.* Microwave Opt Technol Lett 55:100–102, 2013; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.27250

Key words: *microfiber; tapered fiber; interferometer*

1. INTRODUCTION

Optical microfibers have gained a great interest recently due to their interesting optical properties such as tight optical confinement, large evanescent fields, strong field enhancement, and large waveguide dispersions [1–3], which offer plenty of opportunities for developing microphotonic or nanophotonic components/devices ranging from interferometers, filters, lasers, and sensors. To date, several microfiber fabrication techniques have been developed such as the flame brushing technique [4], indirect flame heating [5], CO_2 laser [6], and electric microheater [7]. The fabricated microfibers are used in producing many photonic structures such as loop resonator, coil resonator, knot resonator, Sagnac interferometer, etc [8, 9]. Due to the small dimensions of microfiber, evanescent wave leakage from the tapered area is sensitive to changes in the refractive index of the surrounding medium. Therefore, microfiber knot resonator (MKR) and microfiber Mach–Zehnder interferometer (MMZI) have gained tremendous interest recently for sensors and modulators applications.

In this article, the characteristic of microfiber hybrid structure that comprises MKR and MMZI in series is demonstrated for the first time of our best knowledge. This structure is assembled using a thin microfiber with 1 μm diameter, which was fabricated using a flame-brushing technique.

2. THEORY

Figure 1 shows the schematic illustration of the proposed microfiber hybrid structure which consists of MKR and MMZI in serial arrangement. As shown in the figure, the lightwave E_0 enters MMZI and is split into two fractions represented by E_1 and E_2. For a lossless model,

$$E_1 = (1-\kappa_1)^{1/2}E_0 \quad (1)$$

$$E_2 = j\kappa_1 E_0 \quad (2)$$

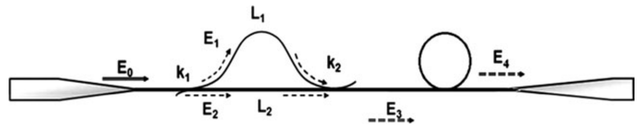

Figure 1 Schematic illustration of the microfiber hybrid structure.

where κ_1 is a coupling ratio of the first coupling junction of MMZI. E_3 is the lightwave at second coupling of MMZI consisting of combination waves E_1 and E_2 after experiencing phase shift βL_1 and βL_2, respectively. Thus, E_3 is given as;

$$E_3 = j{\kappa_2}^{1/2}E_1 e^{j\beta L1} + (1-\kappa_2)^{1/2}E_2 e^{j\beta L2} \quad (3)$$

where κ_2 is a coupling ratio of the second coupling junction. Substituting Eqs. (1) and (2) yield:

$$E_3 = E_0[j{\kappa_2}^{1/2}(1-\kappa_1)^{1/2}e^{j\beta L1} + j{\kappa_1}^{1/2}(1-\kappa_2)^{1/2}e^{j\beta L2}]$$

which can be simplified as:

$$E_3 = E_0[A + B\ cos(\phi)]^{1/2} \quad (4)$$

where $\phi = \beta(L_1 - L_2)$ and A and B are arbitrary constants. The output lightwave from the MKR is then given as:

$$E_4 = T_{\text{KR}}E_3 \quad (5)$$

where T_{KR} is the transfer function of MKR, which was explained in detail by Sumetsky et al. [3] as:

$$T_{\text{KR}} = \frac{e^{\frac{-\gamma S}{2}}e^{i\Psi S} - \sin(K)}{1 - \sin(K)e^{\frac{-\gamma S}{2}}e^{i\Psi S}} \quad (6)$$

where γ is the intensity attenuation coefficient and Ψ is defined as:

$$\Psi = \frac{2\pi\eta_{\text{eff}}}{\lambda} \quad (7)$$

K is a coupling constant, S is a length of the microfiber's ring, η_{eff} is an effective index of the microfiber's ring, and λ is a resonant wavelength. Thus, the output transmission amplitude from the hybrid structure can be written as:

$$T = \frac{e^{\frac{-\gamma S}{2}}e^{i\Psi S} - \sin(K)}{1 - \sin(K)e^{\frac{-\gamma S}{2}}e^{i\Psi S}}[A + B\cos(\phi)]^{1/2} \quad (8)$$

Figure 2 Microscope image of the microfiber hybrid structure consisting of MMZI and MKR. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

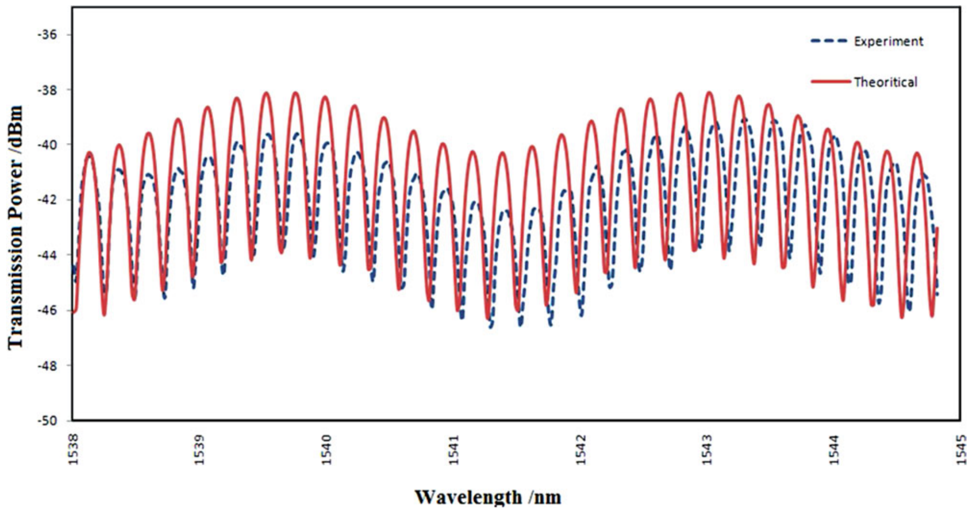

Figure 3 The resonant spectrum of the proposed microfiber hybrid structures obtained from the experiment and theoretical analysis. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

3. EXPERIMENT

At first, an adiabatic microfiber was made by heating and stretching the uncoated SMF using a flame brushing technique. In this process, a SMF-28 fiber was fixed in the linear stages of our taper fabrication rig, and the transmission was monitored using an amplified spontaneous emission (ASE) source and an optical spectrum analyzer (OSA). The fiber was tapered to a microfiber of the desired diameter of 1 μm. The loss after tapering was always less than 0.05 dB. The microfiber is cut into two unequal sections, the longest one is used for assembling the knot by micromanipulation under an optical microscope. The freestanding end of the fiber is first assembled into a relatively large loop about a few millimeters in diameter, which is then tightened into a smaller knot by pulling the free end of the fiber. It was important not to tug the microfiber, though it could readily be flexed without damage. After this manipulation, a microknot is obtained and the remaining microfiber is used to construct MMZI. By using tweezers, this part was vertically bent while another section of the microfiber was stretched straight horizontally and coupled to the earlier part. The bent arm was then manipulated under a microscope using tweezers with the help of van der Waal and electrostatic forces to construct the MMZI. By careful micromanipulation, two evanescent couplers between two microfiber parts can be formed, resulting in the microfiber assembled MMZI.

Figure 2 shows the image of the fabricated hybrid structure. The broadband source from ASE is launched in the microfiber and enters in the first structure which is MZI as shown in Figure 2. The light is dividing into two fractions at first coupling junction and combined at second coupling junction and propagates through MKR. The remaining fraction of the beam propagates through the knot resonator where a portion of beam oscillates in the ring cavity. The output light is characterized by an OSA.

4. RESULTS AND DISCUSSION

Figure 3 shows the output resonance from the hybrid structure, which is compared with the theoretical fitting curve obtained from Eq. (8). The hybrid structure consists of MKR with a ring diameter of 2 mm and MMZI structure with a shortest arm's length of 3.5 mm with distance between the structures being 10 mm as depicted in Figure 2. As seen in Figure 3, dual optical resonance is generated when the light travels through both of the structures. The first resonant is attributed to the MMZI that has a much higher free spectral range (FSR) of 3.1 nm with the extinction ratio of 3 dB. The second resonant has a FSR of 0.24 nm and extinction ratio of 5 dB, which is generated by the MKR. It is observed that the experimental spectrum is in good agreement with the theoretical spectrum. Based on theoretical analysis from Eq. (8), the parameters that involved MKR are the intensity attenuation, $\gamma = 240$ and coupling coefficient, $K = 0.17$. For MMZI, the parameters involved are the path length difference for both of the arms, which is 0.5 mm and the values of constants A and B which are 0.8 and 0.2, respectively. It is obviously shown in Figure 3 that the experimental and theoretical values for the extinction ratio are slightly different. This is most probably due to various factors, such as the difference in coupling coefficient used as well as environmental disturbances such as moving surround air and contamination. FSR of the second resonator can be easily tuned by tightening the knot. Optical resonance is well maintained when the knot is immersed in water or supported on a low-index substrate. We believe that the hybrid structure demonstrated here will find applications in various fields such as sensing, optical processing, and active devices.

5. CONCLUSION

A microfiber hybrid structure consisting of MKR and MMZI in series is successfully demonstrated by micro-manipulating of a thin microfiber. The microfiber is fabricated using a flame brush technique to achieve a waist diameter of 1 μm. The hybrid structure generates a spectrum with dual resonance due to the combination of MKR and MMZI. The MMZI resonant exhibits a much higher FSR of 3.1 nm with the extinction ratio of 3 dB. The MKR resonant has a FSR of 0.24 nm and extinction ratio of 5 dB. The experimental result is in good agreement with the theoretical fitting spectrum.

ACKNOWLEDGMENTS

This project was funded by the MOSTI under Brain-Gain program (Grant No. 5302031067) and the MOHE under HIRG (Grant No: HIR-MOHE D000009-16001).

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DUAL BAND-NOTCH SLOT ANTENNA BY USING A PAIR OF Γ-SHAPED SLITS AND Ω–SHAPED PARASITIC STRUCTURE FOR UWB APPLICATIONS

Nasser Ojaroudi[1] and Mohammad Ojaroudi[2]
[1] Department of Electrical Engineering, Ardabil Branch, Islamic Azad University, Ardabil, Iran
[2] Young Research Club, Ardabil Branch, Islamic Azad University, Ardabil, Iran; Corresponding author: m.ojaroudi@iauardabil.ac.ir

Received 30 April 2012

ABSTRACT: *In this article, we present a novel design of dual band-notch printed slot antenna for ultrawideband (UWB) applications. The antenna consists of a square radiating stub and a ground plane structure with two Γ-shaped slits and Ω-shaped parasitic structure, which provides a wide usable fractional bandwidth of more than 145% (3.04–17.13 GHz). To increase the impedance bandwidth of the ordinary slot antenna, we use two L-shaped parasitic structure in the ground plane that with this structure UWB frequency range can be achieved. Additionally, using two Γ-shaped slits, a single frequency band-stop performance can be achieved, also to create the second notch frequency, we combine an inverted U-shaped strip with two L-shaped parasitic structure, that using this additional inverted U-shaped strip, Ω-shaped parasitic structure can be created. Simulated and measured results obtained for this antenna show that the proposed slot antenna offers two notched bands, around 3.67–4.13 GHz and 5.09–5.97 GHz, covering all the 5.2/5.8 GHz WLAN, 3.5/5.5 GHz WiMAX and 4-GHz C-band range. The antenna has a small dimension of 20 × 20 mm^2.* © 2012 Wiley Periodicals, Inc. Microwave Opt Technol Lett 55:102–105, 2013; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.27223

Key words: *microstrip-fed slot antenna;* **Γ***-shaped slit;* **Ω***-shaped parasitic structure; ultrawideband applications*

1. INTRODUCTION

Communication systems usually require smaller antenna size to meet the miniaturization requirements of radio-frequency units [1]. In ultrawideband (UWB) systems to improve the impedance bandwidth which do not involve a modification of the geometry of the planar antenna have been investigated, and growing research activity is being focused on them. As important compact UWB antennas, printed slot antennas have attracted more and more attention. Consequently, a number of planar slots with different geometries have been experimentally characterized [2–5].

In this article, a new dual band-notched microstrip-fed slot antenna is presented. In the presented antenna, a pair of L-shaped parasitic structures were used for enhance of bandwidth and two Γ-shaped slits with Ω-shaped parasitic structure on the ground plane applied to generate dual bad-notch function. The size of the designed antenna is smaller than the UWB antennas with band-notched function reported recently [2–5]. Simulated and measured results are presented to validate the usefulness of the proposed antenna structure for UWB applications.

2. ANTENNA DESIGN

The presented small slot antenna fed by a 50-Ω microstrip line is shown in Figure 1, which is printed on an FR4 substrate of thickness 0.8 mm, permittivity 4.4, and loss tangent 0.018. The basic slot antenna structure consists of a square stub, feed line, and ground plane. The square stub is connected to a 50-Ω microstrip feed line. On the other side of the substrate, a conducting ground plane is placed. The proposed antenna is connected to a 50-Ω SMA connector for signal transmission.

In this design, the conductor-backed plane is playing an important role in the broadband characteristics of this antenna, because it can adjust the electromagnetic coupling effects between the radiating stub and the ground plane, and improves its impedance bandwidth without any cost of size or expense [6]. Therefore, to achieve a new additional resonance frequency and gave a bandwidth enhancement performance, we use two L-shaped conductor backed plane on the ground plane.

To design a novel antenna, in this study, the Γ-shaped slits in the ground plane perturb the resonant response and act as half-wave filtering element to generate a first notch frequency. At the first notch frequencies, the current flow is more dominant

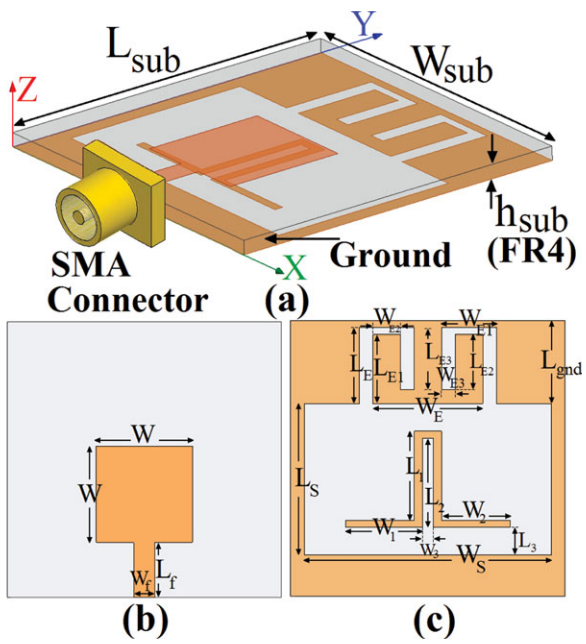

Figure 1 Geometry of the proposed microstrip-fed slot antenna, (a) side view, (b) bottom view, and (c) top view. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]