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Realization of a Novel $1 \times N$ Power Splitter With Uniformly Excited Ports

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***Abstract*— The first experimental demonstration of a novel ring resonator-based $1 \times N$ optical power splitter is reported. We fabricate the device on a Si_3N_4 waveguide platform utilizing a bonded thermal oxide upper cladding. Fiber coupling and near-field-imaging experiments at 1550 nm show that a 1×16 power splitter achieves very low excess loss of 0.9 dB in addition to excellent uniformity of 0.4 dB. The resonances of the device show a loaded quality factor of 6 million and finesse of 100. The device is promising for high-port-count power splitters without the need for cascaded stages. We also discuss applications requiring the wavelength selectivity of the device.**

***Index Terms*— Optical resonators, optical waveguides, power dividers.**

I. INTRODUCTION

LOW LOSS, uniform optical power splitting is needed for increasingly complex optical networks and photonic integrated circuits. Typical power splitters, such as Y branch, multimode interferometer (MMI), and star couplers, can suffer from poor uniformity and higher excess/insertion loss as the number of ports increases [1]–[3]. A system distributing a large number of clock signals with optical interconnects could benefit from lower losses and higher uniformity across ports [4], [5]. Future passive optical networks requiring wavelength and time division multiplexing (hybrid-PON) across multiple FTTx nodes could gain additional benefit from a device with wavelength selectivity [6]. In this letter, we demonstrate the realization of a novel 1×16 power splitter using a ring resonator. We realize this structure in a low loss, CMOS compatible Si_3N_4 optical waveguide platform [7] to achieve a high splitting ratio and uniform outputs that can be scaled even further. While our current design is not directly compatible with data communication applications, it is very useful for narrow linewidth laser applications as well as arbitrary splitting ratios, such as in arrayed waveguide gratings (AWG) [8], to be discussed later.

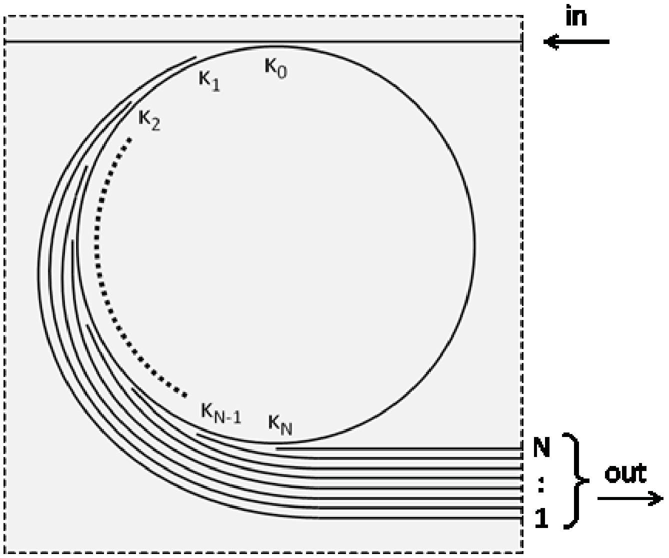

Fig. 1. Schematic for a $1 \times N$ ring resonator-based power splitter.

II. DEVICE DESIGN AND FABRICATION

Fig. 1 illustrates the layout for a general $1 \times N$ wavelength selective power splitter. To demonstrate the usefulness of this device, we fabricate a 1×16 power splitter designed after the theoretical basis in [9]. $N+1$ directional couplers are added tangent to a waveguide ring resonator. To design a critically coupled system in which we can reduce the excess loss, we use the following design rule

$$\tau_0^2 = \gamma^2 \prod_{i=1}^{N} \tau_i^2 \tag{1}$$

where γ is the round trip propagation loss in the ring and $\kappa_0(\tau_0)$, $\kappa_i(\tau_i)$ denote the amplitude coupling (transmission) of the input and i^{th} output port, respectively. To achieve uniform coupling, we match the outputs at two neighboring couplers such that

$$\frac{P_{i+1}}{P_i} = \frac{\kappa_{i+1}^2}{\kappa_i^2} \gamma^{\frac{\Delta\theta}{\pi}} \tau_i^2 \tag{2}$$

where $\gamma^{\frac{\Delta\theta}{\pi}}$ is the propagation loss from the $i+1$ to the i-th directional coupler spaced by $\Delta\theta$ radians. To design a perfectly uniform splitter such that (2) equals unity, each coupler must be accurately fabricated to a designed coupling strength, which can be difficult to control. Our strategy is to reduce the coupling strength to avoid any large mismatch or

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nonideality and make identical output couplers. Fabrication using a resonator with Q values in excess of 1 million [10] allows us to assume $\gamma^{\frac{\Delta\theta}{\pi}} \sim 1$, and finally choose $\kappa_0^2 \approx N\ \kappa_i^2$. According to calculations based on a designed κ_0/κ_i of 2%/0.1%, the theoretical nonuniformity is < 0.1 dB when the waveguide loss is <0.5 dB/cm. Operation at 1550 nm was targeted and the directional couplers' optical bandwidth over which (1) would apply was not measured in this study.

Fabrication of a 1 × 16 ring resonator power splitter begins with a silicon substrate having 15 μm of thermal oxide. A 45 nm Si_3N_4 thin film is then deposited via low pressure chemical vapor deposition (LPCVD) and contact lithography defines the 7 μm wide waveguides. 9.8 mm radius rings (corresponding to 3.3 GHz free spectral range (FSR)) are fabricated to reduce bending loss due to the low index contrast of Si_3N_4/SiO_2 [10]. Three 1.1 μm layers of SiO_2 are deposited via LPCVD with a tetraethylorthosilicate precursor, annealed for 3 hours at 1150 °C, and then the sample is chemically mechanically polished. After this step, a second silicon substrate with 15 μm of thermal oxide is bonded above the waveguides after both surfaces are activated in O_2 plasma. A final anneal step is performed at 950 °C to strengthen the bond. The wafer bonding process was chosen over plasma enhanced CVD in an attempt to avoid hydrogen impurity bond absorption tones as well as less film deposition induced stress. Further details on the fabrication can be found in [7]. Fig. 2 is a photograph of a fabricated device (outer ring) without the top silicon substrate.

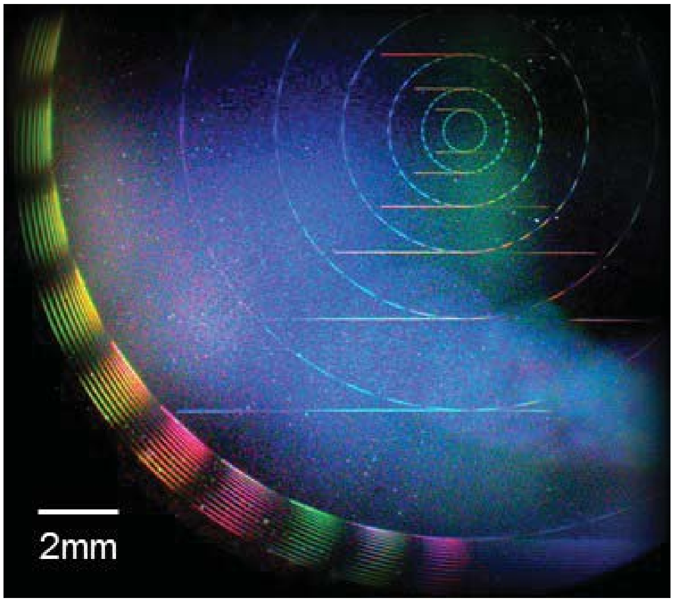

Fig. 2. Photograph of the Si_3N_4 ring resonator power splitter showing most of the 16 output drop ports along the outer edge.

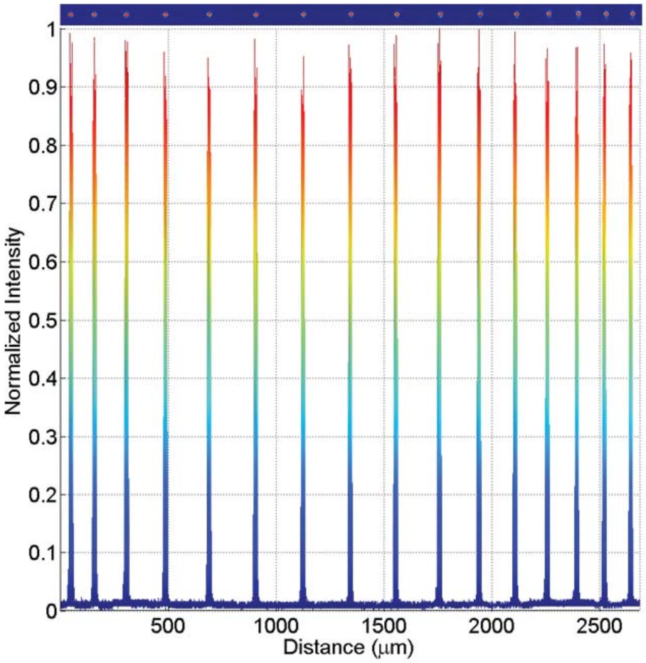

Fig. 3. Near-field intensity map of the 16 output port facets. Nonuniform output waveguide separation was allowed in the design.

III. Measurement and Results

To insure operation of the 1 × 16 ring resonator power splitter, two measurements were performed. In order to measure resonators with less than 100 MHz bandwidth, a 1550 nm narrow linewidth tunable laser source (~100 kHz, Agilent 81640A) was used for near field imaging and spectra analysis. For both measurements, the input polarization was controlled to excite the fundamental TE mode, which exhibits the highest extinction ratio and power coupling efficiency. First, a near field image of each output facet was taken using a 20× objective, collimating optics, and an infrared camera. The stitched images of all 16 ports are shown in Fig. 3, where an intensity mapping yields a uniformity of < 0.4 dB.

Second, to study the excess loss as well as confirm the uniformity, cleaved SMF28 optical fibers were butt coupled to the waveguides. Fiber alignment was performed with piezo translation stages and index matching fluid was used to decrease facet loss and reflection. The coupling loss was measured in reference to fiber to fiber coupling and found to be 1.4 dB/facet assuming negligible straight waveguide loss. The laser was tuned through multiple resonances and a high speed oscilloscope was triggered to capture the through and drop port spectra. Each drop port was measured and assumed to have uniform collection efficiency. A typical spectrum of the through port (red curve) and one output port (blue curve) is shown in Fig. 4, which has a measured drop port extinction ratio of 25 dB and bandwidth of 33 MHz. The corresponding finesse and loaded Q are 100 and 6 million, respectively.

The power measured on resonance at each port is normalized to the through port transmission off resonance (≈1 for high Q). After subtracting the intrinsic splitting loss of 12 dB (1/16), the ring power splitter shows excess loss of 0.9 dB and maximum to minimum uniformity of 0.4 dB. Most of the nonuniformity is due to ~0.2 dB alignment error when butt coupling the fiber and waveguides. The somewhat long propagation distance of ~5 cm at 1 dB/m (conservative estimate from loaded Q) yields a negligible loss of < 0.05 dB that is within our measurement error. The results are plotted in Fig. 5 and compared to typical 1 × 16 MMI splitters,

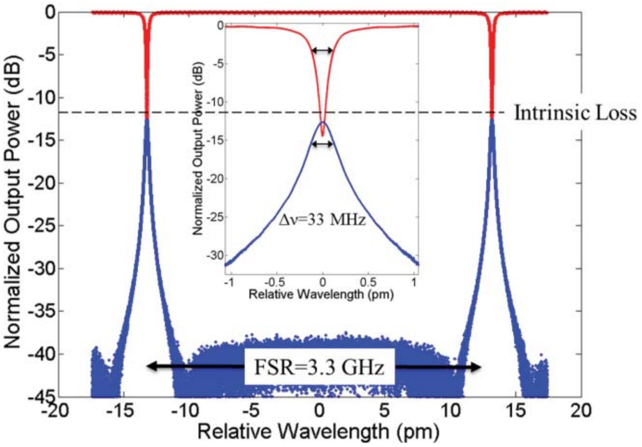

Fig. 4. Red: optical spectrum of the through port. Blue: a typical output drop port.

Y branches, and 19 × 19 star couplers (excited from the center input waveguide). There is good improvement of 0.3 dB excess loss and 0.2 dB uniformity over cascaded Y branch power splitters [1]. More recent cascaded Y branch power splitters written with deep UV stepper lithography show 0.2 dB uniformity improvement, yet suffer from a higher insertion loss by 1.3 dB [11]. When compared to MMI and star couplers, there is a substantial improvement in excess loss and uniformity of 1.8 dB and 1.1 dB, respectively [12], [13]. It should be noted that the MMI in [12] could have a lower insertion loss by increasing the width of the MMI, as shown in [14]. Additionally, recent AWG devices on this platform have shown very low excess loss of 0.5 dB using 2 star couplers with 16 channels [15]. Overall, the ring power splitter performs nearly the same as conventional broadband power splitters in terms of excess loss and uniformity, but has some special features to be discussed in the next section.

IV. APPLICATIONS

The ring based power splitter has some unique features as compared to the conventional splitters shown in Fig. 5. First of all the bandwidth is narrow and the transmission spectra show a set of discrete peaks, evenly spaced at the FSR of the ring. Although such narrow-band transmission rules out applications like data- and telecommunication routing, it is perfectly suitable for fields where spectrally pure laser lines and combs are required, e.g., in microwave photonics, metrology, biophotonics, and as a source for (D)WDM systems.

A second unique feature is that the splitting ratio can be arbitrarily chosen by tuning the directional coupler strengths of the N outputs. This adds significant flexibility over the power splitters mentioned earlier. As an example, a ring based power splitter can replace a star coupler in an AWG. Such star couplers are inherently high loss due to the finite lithography and etch resolution [8]. Ring-based power splitters can be designed to impose a Gaussian profile over the array arms, ensuring low loss and low-crosstalk performance. When an integer FSR of the ring is matched to the AWG channel spacing, consecutive narrow passbands end up in adjacent channels.

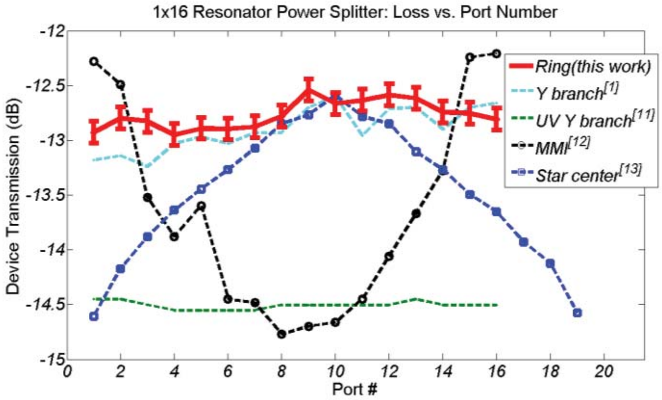

Fig. 5. Transmission and uniformity device comparison between the 1 × 16 ring resonator power splitter of this letter and typical Y branch, MMI, and star couplers seen in literature.

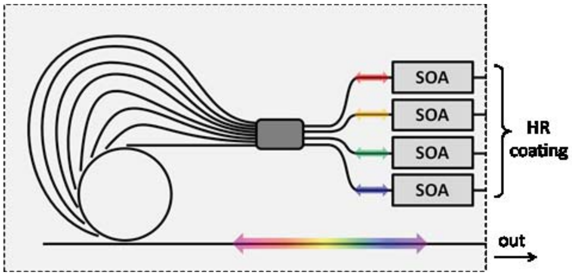

Fig. 6. Schematic of a narrow-linewidth multiwavelength laser. SOAs provide the gain, and the cavity is formed by the facets mirrors.

A particularly interesting application of such an AWG is a multi-wavelength or digitally tunable laser [16], [17]. The concept is schematically shown in Fig. 6. The N outputs of the ring splitter feed the array arms which have a length difference ΔL corresponding to an integer multiple of the ring FSR. A star coupler can be used to combine the array arms, just like a conventional AWG [8]. The star coupler should be used here since the resonance filtering is already achieved with the ring power splitter and using 1 broadband star coupler will avoid alignment of 2 narrowband splitters. The laser cavity is then defined by the facets. By individually biasing the semiconductor optical amplifiers (SOAs) in the output channels, lasing is obtained at the wavelength corresponding to the AWG filter position. Due to the narrow AWG bandwidth, resulting from the high Q ring, very narrow linewidths are feasible. Moreover the wavelength grid is defined by the ring and mode-hopping is eliminated. We are currently further investigating this design.

V. CONCLUSION

We demonstrate a novel splitter architecture based on a ring resonator that offers a uniform, low loss solution to wavelength selective power splitting. The fabricated devices show excess loss of 0.9 dB and uniformity of 0.4 dB across all 16 ports. In comparison to broadband power splitters, this approach offers improved uniformity and excess loss in a wavelength selective device that does not require cascaded stages. The narrowband nature of this device makes it especially useful for systems requiring high spectral purity, such as frequency combs. The layout and fabrication also make this device easily scalable to larger number of output ports while maintaining good uniformity.

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