Wavelength-independent coupler from fiber to an on-chip cavity, demonstrated over an 850nm span

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Abstract: A robust wide band (850 nm) fiber coupler to a whispering-gallery cavity with ultra-high quality factor is experimentally demonstrated. The device trades off ideality for broad-band, efficient input coupling. Output coupling efficiency can remain high enough for practical applications wherein pumping and power extraction must occur over very broad wavelength spans.

OCIS codes: (140.4780) Optical resonators; (060.1810) Couplers, switches, and multiplexers

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15. Yet, one should calculate how wide is the band in which phase match is maintained in his specific configuration.

Whispering gallery devices based on silica have attained remarkably high Q factors [1] and also in formats that enable fabrication on a silicon chip [2]. High Q factors in conjunction with micro-scale mode volumes, provide for immense resonant enhancement of weak input signals. This has enabled demonstration of a variety of nonlinear oscillators [3, 4]. Recently, very broad band frequency tripling from IR to visible has also been demonstrated in these devices [5]. In all of these applications, the coupling technology has been the silica fiber taper [6-8] .

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These devices provide high-ideality coupling to and from the resonator over fairly broad wavelength spans. Third-harmonic generation, however poses a unique challenge to these devices as whispering gallery and fiber taper dispersion do not track well over such wavelength spans.

In this paper we demonstrate a bent-taper coupler whose design is intended to match closely toroidal whispering galleries. This, in turn, endows this device with enhanced coupling bandwidth. Illustrations and micrographs of both a loop coupler and a conventional straight-taper coupler are provided in Fig. 1. The key idea in this device is to provide a more symmetrical coupling geometry in which a tightly-bent coupling mimics the form factor (for dispersion) of the toroidal whispering gallery. Efficient-input coupling to microtoroid resonators over spans as large as 850 nm is demonstrated. This enhancement is achieved, in part, by compromise with output coupling efficiency and overall ideality, which are not as high as with normal fiber tapers. Nonetheless, this compromise can result in acceptable output coupling efficiency over very broad wavelength spans, without resorting to other, more complex coupling approaches (e.g., multiple taper couplers).

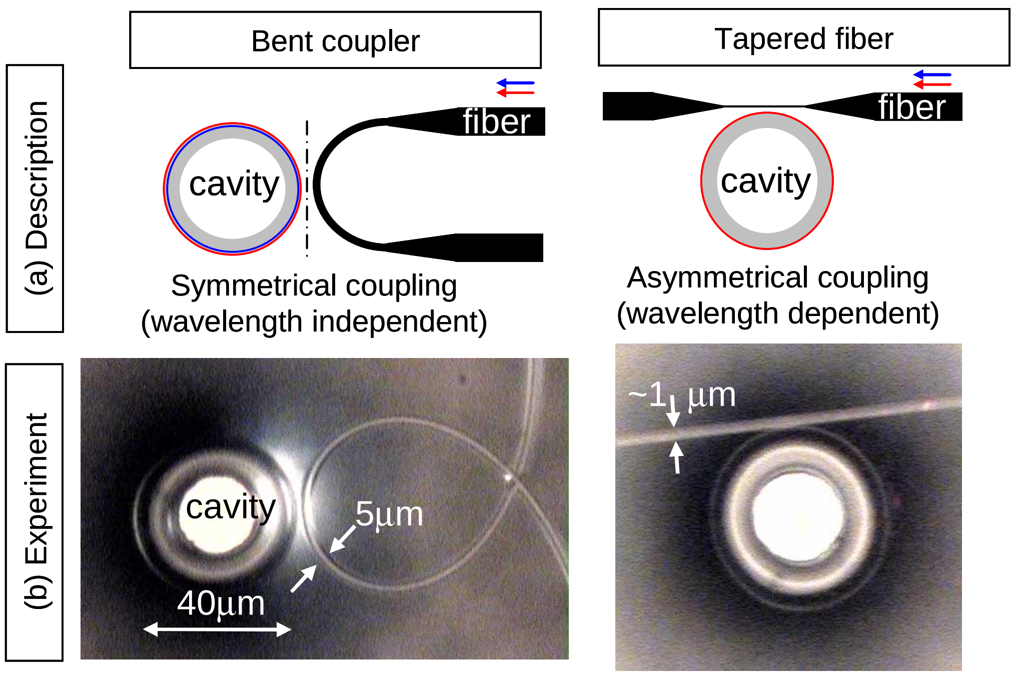

Fig. 1. Comparison between tapered-fiber coupler and bent taper coupler. (a) Schematic description. (b) Micrograph of the cavity and coupler region.

The bent coupler is made from a standard fiber through conventional flame pulling, followed by pushing of the resulting tapered fiber (~1mm while flame is off). This process is then followed by twisting of the fiber (in order to induce a loop) and then pulling (in order to reduce the loop radius). Mechanical stress in the bent coupler is released by thermal annealing of the looped structure.

The fact that the geometry in the bent fiber now mimics the toroid-cavity geometry (in the relevant coupling region, Fig. 1(a), (b) LHS) implies that the propagation velocity is also similar in these two symmetrical sides of the coupler. In particular, both geometrically (curvature and thickness) of the bent coupler is better matched to the toroidal cavity so that waveguide induced dispersion tends to track better than for the case of a straight and narrow taper. In exchange for this improved dispersion matching, the bent coupler, owing to its

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greater thickness (versus a straight coupler), will support multiple higher-order transverse modes. Although these modes do not interfere with coupling from the coupler to the resonator (as this is determined by the temporal frequency), the presence of these modes does interfere with output coupling. As described experimentally and theoretically [8, 9], these modes reduce coupler ideality by introducing parasitic output coupling. On the other hand, in certain applications reduced output coupling can be tolerated. Furthermore, we note that extremely narrow, minor diameter toroids would be well suited to bent couplers with narrow diameters. In this case, there should be little or no loss of ideality while attaining excellent broad-band phase match. These devices are a subject of future study.

Figure 2 contains data showing operation of a bent coupler. Operation in the IR is presented in Fig. 2(a) (LHS) (where typical coupling efficiencies of 94% are measured) and in Fig. 2(b) (LHS) at a wavelength more than twice as short. The fact that we used a single mode fiber in the 1.5 micron band implies that some of the visible power in this measurement is in a high-order transverse mode. It is believed that this is the reason the coupling efficiency in the visible (Fig. 2(b) LHS) is slightly lower than in the IR. In the future, by using single-mode fiber for the shortest wavelength, it is expected to further improve efficiency. The quality factor is measured with the same bent coupler to be 24 and 23 million in the IR and visible, respectively, by monitoring the resonance linewidth (Fig. 2(a), (b) LHS, insets). We performed all linewidth measurements in the under-coupled regime. It is visible at the insets in Fig. 2 that the linewidth is narrow enough to resolve a fine splitting between the clockwise and counter clockwise circulating modes [10].

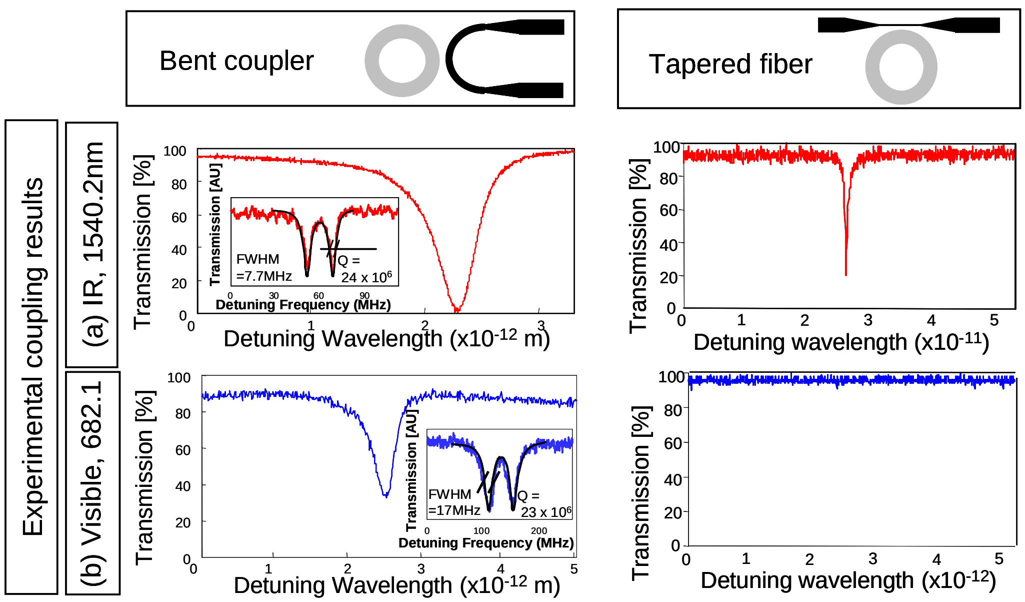

Fig. 2. Comparison between tapered-fiber coupler and bent taper coupler, experimental results. (a) Coupling at IR (1540.2nm). (b) Coupling at visible (682.1nm). Insets describe the transmission in the under-coupled regime and are used for measuring the resonance width. The linewidth is narrow enough to resolve a fine splitting between the clockwise and counter clockwise modes.

We now compare experimentally the wavelength-independent-nature of the bent-taper coupler with that of the straight-taper coupler. Pulling a straight-taper coupler to be phase-matched in the IR [Fig. 1b RHS] enables high quality factor (Q= 24 million) and efficient coupling (80%) at this specific wavelength [Fig. 2(a) RHS]; yet, as expected, this coupler does not function at all in the visible [Fig. 2(b) RHS]. In fact, there was not even a small sign of visible resonance

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when using the straight taper in the wavelength region of the previously measured visible resonance.

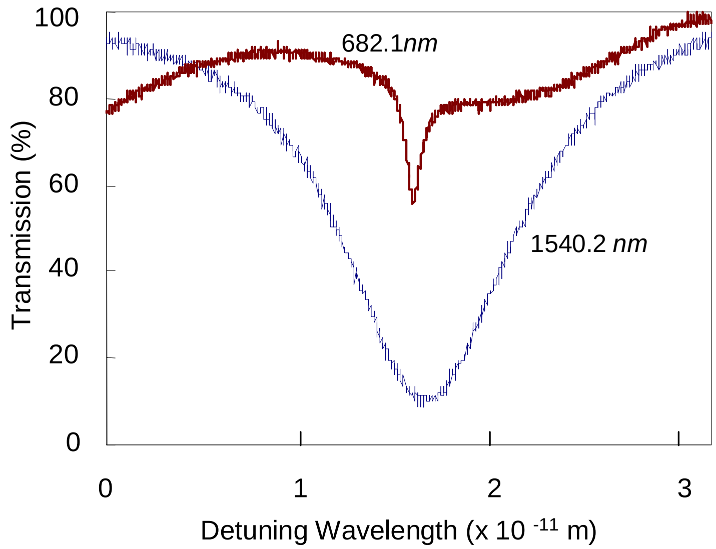

Fig. 3. Simultaneous coupling with bent coupler over 850nm span

Because the required coupling gap, itself, scales with wavelength, optimal coupling in visible and IR requires some adjustment of the coupling gap. However, using a single gap distance, it is possible to obtain coupling (albeit not optimal) at extreme wavelengths as demonstrated in Fig. 3.

An important question is the influence of high-order modes on the coupling process. The reason is that when light is coupled out of the cavity, radiation can be coupled to high-order modes of the coupler that will be afterward lost upon entering the single-mode fiber. To quantify coupling to high-order modes, the coupler ideality is defined as the amount of power coupled to the desired mode (the fundamental coupler mode) divided by the amount of power coupled into all modes. Ideality can be deduced by experimentally measuring transmission while changing the coupler-to-cavity distance as explained in [8, 11]. Experimentally performing such a transmission–versus-distance measurement (Fig. 4) allowed us to infer ideality better than 60% for the over-coupled regime [12] and ideality better than 40% for the under-coupled region [13]. The physical reason that ideality decreases with coupling distance is that high-order modes extend (evanescently) from the coupler to a greater distance which is longer than that of the fundamental mode.

Previously-studied straight-taper couplers do not suffer from coupling to high-order modes and achieve remarkably high idealities over bandwidths of approximately 100 nm [8]. However, as noted above, these devices exhibit phase mismatch over broad tuning ranges. As such the bent coupler approach provides a complementary tool in cases where ideality can be traded-off against bandwidth.

We also note that coupling to high-order modes in the bent coupler is relevant only to coupling out of the cavity. Coupling into the cavity is not affected at all by high-order modes since temporal resonance constrains a single target mode at the wavelength of operation.

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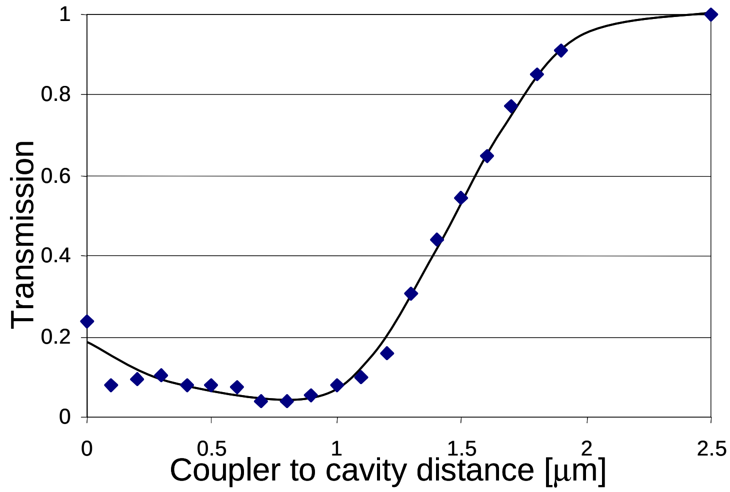

Fig. 4. Experimental measurement of the bent-coupler transmission Vs. coupling distance (squares); the line is a guide for the eye. Cavity external diameter is 32 µm with minor diameter of 6 µm, coupler outer diameter is 37 µm with minor diameter 3.5 µm. Optical quality factor is 22 million and wavelength is 1542.4 nm.

It is important to note that the bend here is only tens of microns in diameter and functions to allow wavelength-independent coupling. This is in contrast with previous work (e.g., reference [14]) in which a mm-scale bend provided a geometrical function of allowing access to flat cavities but had no optical purpose.

It is worth mentioning that the bent coupler in Fig. 1 is not limited for coupling light into toroids, it can also be used for coupling light to spheres or other types of non whispering-gallery-mode cavities [15]. Also, although the main goal here was to build a wavelength-independent coupler, the bent fiber possesses additional advantages. In particular, improved power handling capability is expected since replacing the ~1 μm straight taper with a bent fiber of 10 μm diameter will increase the area through which heat is dissipated by a factor of 100. Additionally, the bent fiber is stronger mechanically.

In conclusion, a wavelength-independent fiber coupler is experimentally demonstrated over an 850nm span. The cross-sectional area of the coupler demonstrated is more than one order of magnitude larger than straight tapers suggesting proportionally better mechanical strength and heat dissipation for high-power applications. This bent coupler is expected to also work throughout the whole silica transparency band (250-2000nm) and opens current technology of ultra-high Q cavities to be fiber accessible for applications and scientific research in a regime spanning from the extreme UV to the IR band.

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