Photonic integrated 4-meter-coil resonator critically coupled from 900 nm to 1600 nm

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Abstract: We demonstrate a silicon nitride photonic-integrated two-point-coupled 4-meter-coil-resonator capable of tunable critical coupling over a 700 nm range, 910 - 1610 nm, with 48 - 77 million intrinsic Q. © 2025 The Author(s)

1. Introduction

Optical resonator reference cavities are a foundational technology in many precision applications, including gravitational wave detection [1], quantum communications [2], atomic clocks [3], low-noise microwave and mmWave [4], and fiber optic sensing [5]. These cavities, carefully engineered silica structures housed in vacuum enclosures, are used to narrow the laser linewidth, reduce optical phase noise, stabilize the carrier, and traditionally occupy a lab-scale footprint. There is great interest in miniaturizing these reference cavities; approaches include WGM resonators [6], micro-rod silica [7], and vacuum gap cavities [8]. Further integration to the chip scale [9,10] using the silicon nitride (Si_3N_4) CMOS-compatible photonic platform is currently of high interest to allow further integration with lasers and other photonics and provide systems-on-chip solutions. Recently, progress in long meter-scale Si_3N_4 integrated coil reference cavities has incorporated two-point coupler tuning of the resonator cavity at multiple wavelengths over a limited range to adjust the coupling condition [11]. There is significant interest in expanding the wavelength range such that a single fabricated stabilization reference cavity can cover the near-IR wavelength range with precision frequency performance across this wide range. Progress in extending the operating wavelength range of silicon nitride (Si_3N_4) ring resonators [11] has shown broadband operation from the L-band down to visible wavelengths. The next step is to develop an integrated resonator that realizes tunability over broad wavelength bands with high Q and noise reduction, paving a path toward octave-spanning coverage.

We report an important new result in integrated optical coil reference cavities, a demonstration of a Si_3N_4 4.0-meter-coil-resonator with a tunable 2-point coupler and a waveguide geometry designed to optimize the tunable coupling capability across a 700 nm wavelength range using a single device. This work demonstrates a photonic-integrated coil-resonator featuring a wavelength tunable 2-point-coupled 4.0-meter-coil, achieving 48-77 million intrinsic Q over 910-1610 nm wavelengths. We demonstrate laser locking at 1320 and 1550 nm and achieve 2.5 to 3 orders of magnitude frequency noise reduction between 1 and ~10 kHz. The novelty in this work is the ability of a single device to resonate at wavelengths that span 700 nm. The tunable two-point coupler and low losses in Si_3N_4 [12,13] are leveraged for the design (Fig. 1(a)), which enables tunable critical coupling over 700 nm of optical bandwidth. To achieve these results, we modify the geometry of the waveguide structure from the structure reported in reference [11] to optimize the tunable coupling capability over 700 nm. This cavity's wide wavelength operating range enables size, weight, and power (SWAP) benefits by reducing the number of cavities that may be required on a chip, but also significant performance benefits for emerging applications such as mmWave and microwave optical frequency division [4] and fiber sensing [5] as well as quantum and atomic applications such as rubidium Rydberg atom applications, ranging from 480 to 1260 nm [14–16]. The operability over a wide wavelength range, paired with the 52 MHz free spectral range (FSR) of the coil resonator, opens the door to many precision applications that cannot be achieved with tabletop reference cavities.

2. Photonic integrated coil resonator design, resonator characterization, and laser stabilization

The integrated resonator employs a tunable 2-point coupler, shown in Fig. 1(a), which is an unbalanced MZI structure with two individual couplers that connect the bus to the ring [11]. The resonator coupling from the two-point coupler is determined by the maximum bus-to-resonator coupling (κ_{max}^2) and a phase section (ϕ) that tunes the effective bus-to-resonator coupling, that is, $\kappa^2(\phi)=k_{max}^2\cos(\phi)^2$ [11]. The κ^2_0 parameter is the power coupling parameter for a single coupler and is influenced by the transverse optical mode profiles in the coupler, which is dependent on waveguide geometry and material properties and is used to calculate the two-point coupler maximum coupling, $\kappa_{max}^2 = 4\kappa_0^2(1-\kappa_0^2)$. The phase tuner and waveguide geometry are engineered to optimize the shape of the waveguide's fundamental transverse electric (TE) mode such that critical coupling can be achieved within the maximum phase tuning capability of the MZI. In particular, we have reduced the coupling gap from 2.5 um to 0.8 um, relative to the near-infrared (NIR) 4-meter-coil device [11], in order to provide sufficient resonator coupling at shorter wavelengths. The narrower coupler gap increases the mode overlap between the bus and coil waveguides, increasing the evanescent coupling at shorter wavelengths. In addition, we design the MZI heater with enough length to achieve a π phase shift within approximately 500 mW of power. Lastly, we have packaged this device, providing thermal stabilization, protection from acoustics and the environment, and fiber pigtails for ease of use.

We characterize this device at various phase tuner powers, as shown for the 1610 nm wavelength in Fig. 1(b). At 1610 nm, near-critical coupling is achieved when 300 mW is applied to the thermal tuner. We performed a similar characterization of our device across a number of wavelengths in the 910 nm to 1610 nm waveband, Fig. 1(d), with quality factors ranging from 48-77 million intrinsic Q. Figure 1(c) shows the losses for the fundamental TE mode we measured at each of these wavelengths.

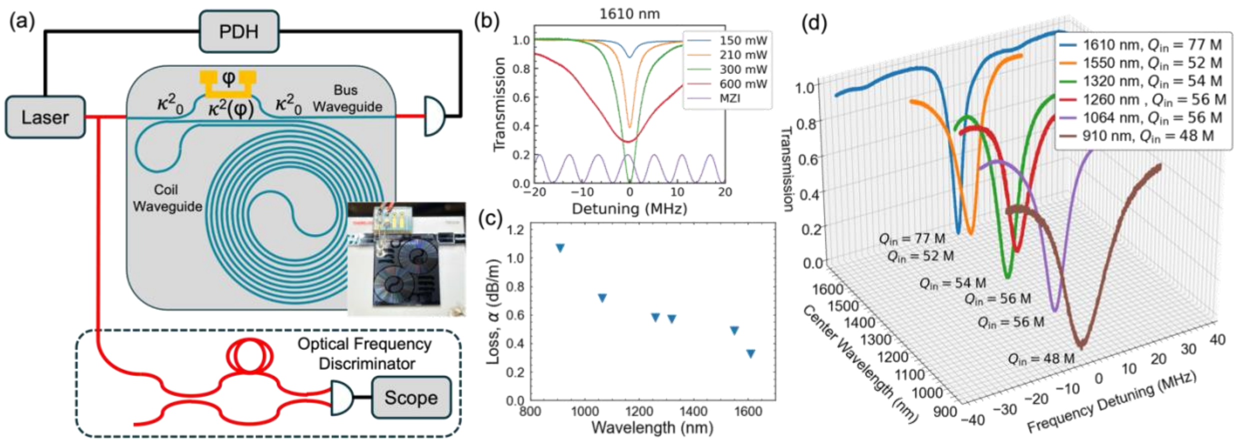

Fig. 1. (a) Laser noise measurement of laser stabilized to a 4-meter-long 2-point coupled coil waveguide resonator. (b) Measured resonator quality factor at 1610 nm for a range of tuning powers applied to the tunable 2-point coupler. (c) Measured waveguide propagation loss for select wavelengths from 910 nm to 1610 nm. (d) Measured resonator quality factor for a range of wavelengths from 910 nm to 1610 nm.

We demonstrate the application of this 4-meter-coil resonator to laser linewidth narrowing at 1320 nm and 1550 nm using the Pound-Drever-Hall (PDH) lock method. A fiber unbalanced MZI with a 1.026 MHz FSR is used as an optical frequency discriminator (OFD) for self-delayed homodyne laser frequency noise measurement at a frequency offset above 1 kHz [17–19]. A schematic of our laser locking setup and frequency noise characterization is shown in Fig. 1(a). At 1550 and 1320, we achieve thermorefractive noise (TRN) limited results (Fig. 2) with 2.5 to 3 orders of magnitude reduction in the 1 to ~100 kHz frequency range. The two-point coupled resonator lowers the C-band and O-band laser integral linewidths by a factor of 9 from 2.3 kHz to 250 Hz and 4 kHz to 289 Hz, respectively. We anticipate that the integral linewidths of the coil-stabilized lasers will be lower, as the frequency noise measurements using fiber OFD exhibit acoustic noise at offsets below 5 kHz.

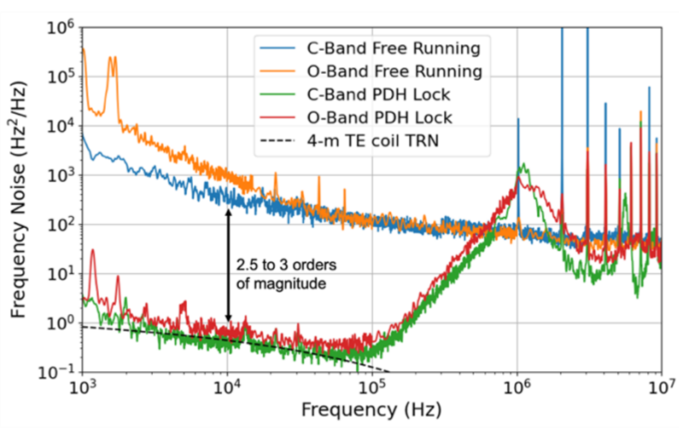

Fig. 2. Measured frequency noise spectrum of 1320 nm and 1550 nm lasers, showing the free-running laser frequency noise spectrum and noise spectrum after PDH locking to the tunable two-point coupled 4-meter-coil resonator.

3. Conclusion and Discussion

We have demonstrated high Q and critical coupling operation in a single tunable 4-meter silicon nitride photonic-integrated coil resonator over a 700 nm wavelength range from 910 nm to 1610nm. The tunable intrinsic quality factor over this wavelength range is 48-77 million Q, and critical coupling is achieved over the operating range. We use this two-point coupled resonator to demonstrate significant linewidth reduction at 1320 and 1550 nm with 2.5 to 3 orders of magnitude frequency noise reduction between 1 and ~100 kHz and reduction of the integral linewidth from the pump by a factor of 9. These results pave a path forward to operation over an octave and into visible wavelengths supporting quantum and atomic applications and moving to programmable devices for systems-on-chip solutions.

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