

Drop-port study of microresonator frequency combs: power transfer, spectra and time-domain characterization

Pei-Hsun Wang,^{1,*} Yi Xuan,^{1,2} Li Fan,^{1,2} Leo Tom Varghese,^{1,2} Jian Wang,^{1,2} Yang Liu,¹
Xiaoxiao Xue,¹ Daniel E. Leaird,¹ Minghao Qi,^{1,2} and Andrew M. Weiner^{1,2}

¹*School of Electrical and Computer Engineering, Purdue University, 465 Northwestern Avenue, West Lafayette, IN 47907-2035, USA*

²*Birck Nanotechnology Center, Purdue University, 1205 West State Street, West Lafayette, Indiana 47907, USA*

* wang1173@purdue.edu

Abstract: We use a drop-port geometry to characterize frequency combs generated from silicon nitride on-chip microresonators in the normal group velocity regime. In sharp contrast with the traditional transmission geometry, we observe smooth output spectra with comparable powers in the pump and adjacent comb lines. The power transfer into the comb may be explained to a large extent by the coupling parameters characterizing the linear operation of the resonances studied. Furthermore, comparison of thru- and drop-port spectra shows that much of the ASE noise is filtered out by transmission to the drop-port. Autocorrelation measurements are performed on the drop-port output, without the need to filter out or suppress the strong pump line as is necessary in thru-port experiments. Passively mode-locked pulses with low background are observed in a normal dispersion microcavity.

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1. Introduction

Optical frequency combs based on nonlinear optical modulation in high quality factor (Q) microresonators, such as toroidal microresonators, crystalline resonators, and waveguide ring resonators, are the subject of considerable attention [1–16]. Through cascaded four wave mixing (FWM) in these high Q devices, the built-up intracavity power enables additional cavity modes to oscillate. In most previous studies a thru-port geometry consisting of a single bus waveguide, fiber, or coupling prism is used to couple light both into and out from the microresonators, while a few experiments utilize a drop-port as an output coupler [2, 3, 5, 11, 17]. Typically, the comb spectrum observed at the thru-port contains a strong peak at the

pump frequency, which often is 20 dB or more above the adjacent comb lines [1, 4, 7–10, 12–16]. Thus, the power transfer into the comb is often poor. Furthermore, the presence of a strong copropagating pump at the thru-port makes it difficult to determine whether or not the intracavity comb field is accompanied by a significant background. To shed light on these issues, here we study comb generation in a silicon nitride microresonator fabricated with a drop-port, a geometry that has been widely used in optical add-drop filters [18, 19]. By observing the output from the drop-port, we can directly probe the comb fields internal to the microring. This avoids a complication inherent at the thru-port, for which the output pump light depends on the interference between the field coupled out of the microresonator and the field directly transmitted from the input bus. Although the introduction of a drop-port does impact the loaded quality factor, it also provides new information.

Our work results in several new findings. First, the comb spectra observed at the drop-port are smooth, with the intensity of the pump line comparable to that of the comb lines. Smooth spectra such as reported here are potentially advantageous for line-by-line pulse shaping studies [20, 21]. Second, the (weak) power transfer into the comb may be explained to a large degree by the coupling parameters characterizing the linear operation of the resonances studied. Third, comparison of thru-port and drop-port spectra shows that much of the amplified spontaneous emission (ASE) noise is filtered out by transmission to the drop-port. Finally, by performing autocorrelation measurements to characterize the time-domain behavior of the combs from the drop-port, we observe direct ultrashort pulse generation, without the need to filter out or suppress the strong pump as was necessary in previous thru-port experiments [9, 10, 13–15]. Although several recent studies have reported ultrashort pulse generation with microresonator-based combs, either directly [14–16] or with external phase compensation via line-by-line pulse shaping [9, 10, 13], this paper is the first, to our knowledge, to experimentally demonstrate ultrashort pulse generation with low background level directly from a microcavity believed to be in the normal dispersion regime.

In the following we would like here to briefly discuss recent literature which bears on the form of the comb field expected in the microresonator. This is especially relevant to the data we will present on low background level pulse generation.

Most theories discussing conditions for comb formation are based on a modulational instability analysis assuming a microresonator characterized by anomalous dispersion, e.g. [12]. Both analytical and simulation studies identify operating regimes consistent with formation of single soliton coupled to a continuous background field inside the resonator [14, 16, 22]. An analytical investigation of mode-locked Kerr combs also predicts a large continuous-wave (CW) background at the thru-port associated with a strong residual pump [23]; the solutions presented explicitly include a CW component internal to the microresonator. Experiments demonstrating generation of soliton-like ultrashort pulses from anomalous dispersion microresonators are reported in [14, 15]. However, the existence of a continuous background field inside the cavity has not been verified. Although experimental spectra do exhibit a strong pump line, this may be associated with the strong pump field transmitted directly from the input waveguide in the thru-port configuration. Time-domain measurements performed at the thru-port do reveal short pulses with low background; however, these experiments rely on filtering out the copropagating pump which inherently eliminates any background field present.

Microresonator-assisted mode-locked lasers, in which a microring is incorporated inside the laser cavity in a drop-port geometry, have been reported in [24, 25]. In these studies the microresonator is also described as having anomalous dispersion. Under stable operating conditions, these systems produced smooth but narrow comb spectra, without evidence of a markedly stronger pump line. However, because the microresonator is seeded by the full multiplicity of intracavity comb lines, the operating regime is rather different than that of usual micro-comb generation studies in which the microresonator is seeded by a single pump line.

A few recent studies discuss comb generation in microresonators characterized by normal dispersion. Theoretical explanations involve modification of the conditions for modulational instability in a cavity with detuned pump frequency [26] and the influence of interactions with other mode families on the local dispersion [27]. In [26] a complex pulse shape with significant background but with a smooth intracavity spectrum was predicted; ref [27], also predicted a smooth spectrum but did not discuss the form of the field in the time domain. A measurement of a smooth comb spectrum was reported in [27] using a thru-port geometry. In contrast, recent simulations predict an intracavity field solution consisting of a dark pulse on a background, with a strong pump line in the intracavity spectrum [16]. Previous time-domain experiments with normal dispersion microresonators [9, 13] did succeed in generating low background level ultrashort pulses through external line-by-line pulse shaping. However, because these studies utilized a thru-port geometry and required attenuation of the strong copropagating pump, they did not provide information on the background level of the intracavity field.

In our present work, we have observed direct generation of ultrashort pulses from microresonators believed to be in the normal dispersion regime. By performing measurements at the drop-port, no attenuation of the pump or other spectral shaping is required. Both spectral data and time-domain data provide clear indication of an operating regime corresponding to ultrashort pulses generated on low or zero background.

The remainder of this paper is organized as follows. Section 2 gives a brief overview of the experimental setup. Section 3 compares comb spectra at thru- and drop-ports and investigates power transfer. Time-domain measurements are presented in Section 4. In Section 5, we conclude.

2. Experimental setup

Figure 1(a) shows a microscope image of the silicon nitride microring resonator with $2\ \mu\text{m} \times 550\ \text{nm}$ waveguide cross-section and $100\ \mu\text{m}$ radius. The gaps between the resonator and the thru-port and drop-port coupling waveguides are both $700\ \text{nm}$. For stable coupling on- and off-chip, lensed single mode fibers are placed into U-grooves as shown in Fig. 1(b) and aligned with the waveguide. We note that although in the current experiments, the thru- and drop-port coupling are symmetric, asymmetric designs with weaker drop-port coupling are also possible. This would lessen the effect on the loaded Q , at the cost of reduced power transfer to the drop-port, which is appropriate if the primary aim is to provide a monitor for the internal comb field.

Figure 1(c) shows the block diagram measurement setup. Measurements of spectra at thru- and drop-ports are performed sequentially using an optical spectrum analyzer (OSA); the lensed fiber is positioned first at one output and then moved to the other, typically with the input lensed fiber fixed. Time-domain measurements were performed using intensity autocorrelation based on second harmonic generation in a noncollinear geometry. For time-domain characterization, the output from the drop-port is sent into an erbium-doped fiber amplifier (EDFA). The amplified output is then sent through a length of dispersion compensating fiber (DCF) and connected to the intensity autocorrelator. The length of the DCF was set by injecting a short test pulse laser from a passively mode-locked fiber laser through the fiber link (starting at the output lensed fiber). The DCF was trimmed to minimize the duration of the autocorrelation trace. The autocorrelation width of the test pulse after the fiber link was $368\ \text{fs}$ full-width at half-maximum (FWHM). This is close to the autocorrelation width ($302\ \text{fs}$) calculated using the optical spectrum after the EDFA with the assumption of flat spectral phase. The slight difference likely results from residual higher-order dispersion. We conclude that for pulse durations down to several hundred femtoseconds, the link is approximately dispersion compensated, so that autocorrelation measurements reflect the actual field at the microresonator.

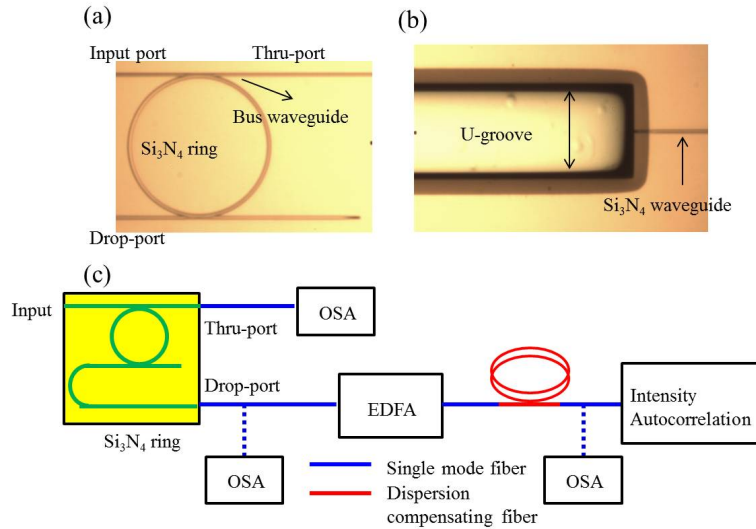


Fig. 1. (a) Microscope image of a 100 μm radius silicon nitride microring with coupling region. (b) Image of a U-groove. (c) Experimental setup for time-domain characterization.

3. Comb spectra and power transfer

A tunable CW laser is amplified and launched into the ring resonator. For our study of comb spectra and power transfer, we investigate two TM resonances, for which the electric field is predominantly polarized perpendicular to the plane of the wafer. The first resonance (TM_1) is a doublet centered at ≈ 1558.4 nm [Fig. 3(a) inset], has intrinsic quality factor (Q) approximately 3.1×10^6 for each of the individual lines, and belongs to a mode family with 1.84 nm average free spectral range (FSR). This splitting of the resonant peak may result from a backward propagating wave induced by scattering from the coupling regions [28] or surface roughness [29]. The second resonance [Fig. 3(b) inset] occurs near 1558.7 nm, has intrinsic Q around 1.0×10^6 , and belongs to mode TM_2 with 1.76 nm average FSR. The modes here are identified by simulating the group index for different modes [30] and comparing the estimated FSR with the experimental one.

Figure 2 shows the measured dispersion (dots) and simulated dispersion (solid lines) including both waveguide and material dispersion within the bandwidth region of interest. The refractive indices for the silicon nitride core and silicon oxide cladding are assumed to be 2.07 and 1.45, respectively. Waveguides with 2 μm width and either 550 nm thickness (as in the current samples) or 765 nm thickness are considered. The simulated TM_1 and TM_2 mode profiles of are shown in the inset of Fig. 2 for 550 nm thickness. Thinner films are expected to exhibit normal dispersion, with anomalous dispersion possible for films thicker than about 700 nm. This prediction is consistent with previous work on dispersion-engineered, anomalous dispersion silicon nitride waveguides for comb generation [4]. We performed measurements of the via frequency comb assisted diode laser spectroscopy [31]. The measurement data are in qualitative agreement with the simulations, indicating normal dispersion for the 550 nm waveguide samples and anomalous dispersion for the 765 nm thick waveguide. Quantitative differences between the simulated and measured dispersion are attributed to uncertainty in the refractive index values, which depend on the film deposition process parameters. Overall, the simulation and measurement results provide strong evidence that the 550 nm thick microring samples investigated in the remainder of this paper are characterized by normal group velocity dispersion.

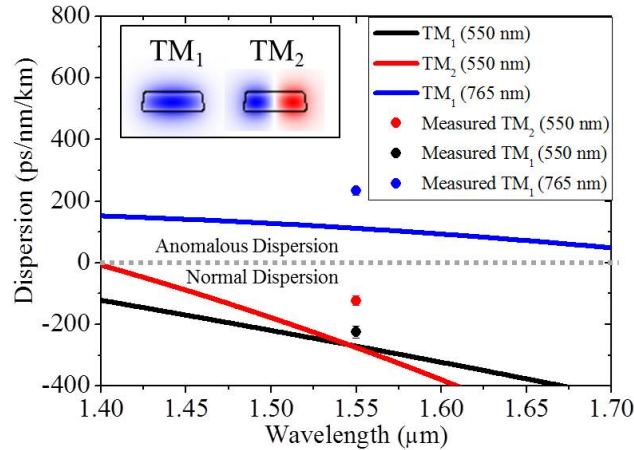


Fig. 2. Measured and simulated dispersion of silicon nitride waveguides for 550 nm and 765 nm film thicknesses. The inset shows the TM_1 and TM_2 mode profiles for 550 nm waveguide thickness. The solid lines show the simulated data while the dots show the measured data. The values in the parentheses in the legend indicate the height of the waveguide.

To generate a frequency comb, the laser is tuned to a resonance from the short wavelength side to achieve a “soft thermal lock” [4, 5, 32]. The pump linewidth is estimated narrower than 20 MHz by beating with a fiber comb source (Menlo Systems). It’s at least three times narrower than the ≈ 64 MHz linewidth of the higher-Q TM_1 resonance. Figure 3 shows the optical spectra observed both from the thru- (blue trace) and drop-port (red trace) at the highest input powers studied: (a) 430 mW at around 1558.5 nm (TM_1 mode) and (b) 680 mW at around 1558.8 nm (TM_2 mode). Here the input power is defined as the power in the input waveguide before the microring. We estimated the power in the waveguide by measuring the input- to thru-port fiber to fiber loss, typically 3~5 dB, and assigning half of this loss to the input side. For the resonances studied here, frequency combs are observed to generate lines spaced by 3 FSRs for the TM_1 mode and 5 FSRs for the TM_2 mode. Both resonances are red-shifted around 0.1 nm due to the thermal nonlinearity under the pumping conditions quoted above.

For the spectra from the thru-port, ASE noise is clearly observed. For spectra measured from the drop-port, the ASE noise between the comb lines is filtered out. An important point is that the drop-port data reveal the power spectrum internal to the microring. Although the power at the pump frequency is much stronger than that of the adjacent comb lines in the thru-port data, in the drop-port data the power at the pump frequency is much closer to that of adjacent lines. Evidently, for the resonances studied, the combs internal to the microring have approximately smooth spectra. For the data of Fig. 3(a), the pump power at the drop-port is 22.6 dB lower than at the thru-port. For the thru-port, the pump is 19.1 dB stronger than the stronger of the adjacent lines, while at the drop-port the pump is actually slightly (1.7 dB) weaker than the stronger adjacent line. For the data of Fig. 3(b), the pump at the drop-port is 12.5 dB weaker than at the thru-port. Compared to the stronger of the adjacent lines, the pump is 16.3 dB stronger at the thru-port but only 5.5 dB stronger at the drop-port. We may conclude that to a large extent, the much stronger pump line observed at the thru-port is related to coupling conditions, not to the actual comb in the ring. Even compared to previous studies employing a drop-port geometry [2, 5, 11], our spectra, particularly Fig. 3(a) – and another example, Fig. 6(a), presented later – exhibit a degree of smoothness in the region around the pump rarely observed. The absence of a strong pump line in our drop-port spectra suggests that at least under some conditions, possibly associated with the normal group velocity dispersion of our devices, the continuous-wave component of the internal field can be small.

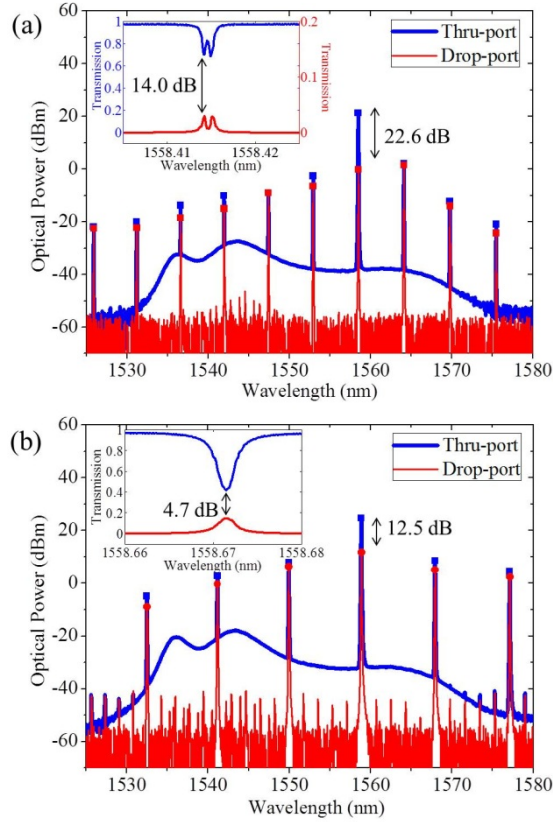


Fig. 3. Measured optical spectra of generated combs from both the thru- (blue trace) and drop-port (red trace) with input power (a) 430 mW at around 1558.5 nm (TM₁ mode) and (b) 680 mW at around 1558.8 nm (TM₂ mode). The insets show the corresponding transmission spectra with low input power; the vertical scale on the left axis of (a) inset shows the drop-port transmission.

Note that aside from the pump line, the output comb lines from the thru- and drop-ports in Fig. 3 exhibit close to the same power levels, except the drop-port lines are reduced by an average of 2.5 dB relative to the thru-port. Since with symmetrical coupling, the comb lines from thru- and drop-ports should have the same power, this implies either the coupling is unintentionally slightly different or the output drop guide has larger loss. To account for this difference, we adjust the estimated drop-port powers upwards by 2.5 dB in the output vs. input power data presented later as Fig. 4.

Since the large fraction of pump power that emerges from the thru-port is attributed to the coupling conditions, it is interesting to consider the coupling effects quantitatively. Following the theory proposed in [33], the coupling parameters could be extracted by fitting the thru-port transmission spectra which can be written as:

$$T_{thru} = \frac{(\lambda - \lambda_0)^2 + \left(\frac{FSR}{4\pi}\right)^2 (\kappa_d^2 + \kappa_p^2 - \kappa_e^2)^2}{(\lambda - \lambda_0)^2 + \left(\frac{FSR}{4\pi}\right)^2 (\kappa_d^2 + \kappa_p^2 + \kappa_e^2)^2} \quad (1)$$

where T_{thru} is the power transmission response at the thru-port, and FSR is the free spectral range in the resonators in wavelength units. κ_e^2 and κ_d^2 are dimensionless coefficients characterizing the power coupled into and out of the microring from the input and drop

waveguide per round trip, respectively, while κ_p^2 is the dimensionless power loss per round trip due to intrinsic loss in the resonator. The fitting results for the two resonances investigated are shown in Table 1. Note that for the TM_1 resonance, the κ coefficients are calculated using the linewidth of a single resonance (short wavelength side) making up the doublet. For both resonances symmetrical coupling is assumed. The power transmission response of the drop-port T_{drop} may be calculated based on the parameters extracted from Eq. (1) and is written as:

$$T_{drop} = \frac{4 \times \left(\frac{\text{FSR}}{4\pi}\right)^2 (\kappa_d^2 \times \kappa_e^2)}{(\lambda - \lambda_0)^2 + \left(\frac{\text{FSR}}{4\pi}\right)^2 (\kappa_d^2 + \kappa_p^2 + \kappa_e^2)^2} \quad (2)$$

Table 1. Coupling and Transmission Parameters

Resonance	Calculated by Coupling Parameters			Transmission Spectra				
	κ_e^2	κ_d^2	κ_p^2	$\frac{T_{thru}}{T_{drop}}$ (dB)	T_{thru}	T_{drop}	$\frac{T_{thru}}{T_{drop}}$ (dB)	Linewidth (pm)
1558.4 nm (TM_1)	1.49×10^{-4}	1.49×10^{-4}	1.57×10^{-3}	14.5	0.70	0.028	14.0	0.7
1558.7 nm (TM_2)	1.41×10^{-3}	1.41×10^{-3}	5.04×10^{-3}	5	0.42	0.142	4.7	2.3

As shown in Table 1, the T_{thru}/T_{drop} values from Eq. (1) and (2) are in close agreement with those observed experimentally, giving confidence in the parameters extracted. We note that for both resonances, the loss in the microring is significantly larger than the waveguide couplings. Hence, the resonances are under-coupled. In this under-coupled regime, the introduction of a drop-port has relatively weak impact on the loaded Q. We also note that the intrinsic loss for the 1558.7 nm (TM_2) resonance is approximately three times higher than that for the 1558.4 nm (TM_1) resonance, consistent with the fact that the fundamental mode usually has lowest intrinsic loss. Finally, from the parameters shown in the Table, we observe that the under-coupling is much more severe for the TM_1 resonance.

We have studied the power distribution in the combs observed at thru- and drop-ports with varying input power. To account for thermo-optically induced resonance shifts, at each input power the pump wavelength is tuned carefully into resonance, which we have defined as the wavelength yielding minimum power transmission from the thru-port (maximum transmission from the drop-port). Figure 4(a) shows the output pump power (black trace) and comb power (blue trace) at the thru-port versus input power for the TM_1 resonance. The input and output powers refer to on-chip powers estimated before and after the microring, respectively. The comb power is obtained by integrating the measured optical spectrum excluding the pump line, while the pump power is determined by integrating over a 1 nm range centered on the pump. Both pump and comb power increase with input power, with the comb showing a threshold effect. The corresponding drop-port results are shown in Fig. 4(b). Unlike the nearly linear pump power curve measured at the thru-port, at the drop-port the pump power clearly saturates (although not abruptly) above the threshold for comb generation.

The TM_2 resonance furnishes another example of pump saturation. Figures 4(c) and 4(d) show the detected output power at the thru- and drop-port versus the input power. Clamping of the pump power in the microring above the comb generation threshold is again observed. Any further increase in the input power beyond threshold leads to an approximately linear rise – at least initially – in the parametric signals (i.e., the frequency combs). This observation suggests saturation of the parametric gain analogous to gain saturation observed in

conventional parametric oscillators above threshold [34, 35]. Similar saturation behavior has also been observed for microresonator frequency combs in the drop-port experiments of [5] and in simulation studies [6].

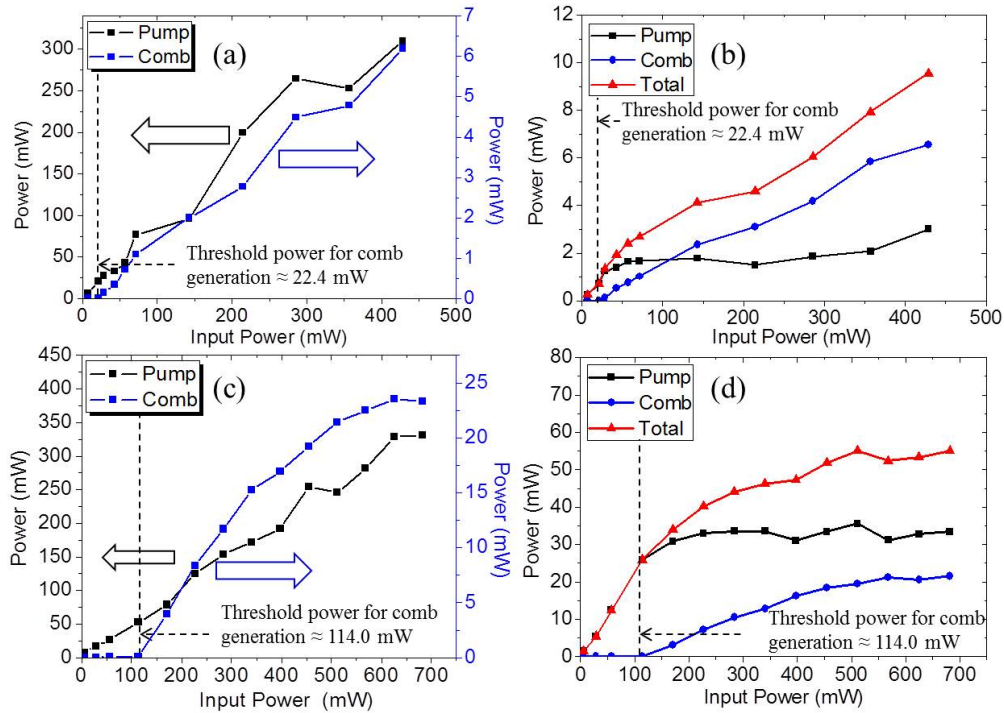


Fig. 4. The detected output power of the pump (black trace) and the comb lines other than the pump (blue trace) versus input power, corresponding to the (a) thru- and (b) drop-port at 1558.4 nm (TM_1) resonance while (c) and (d) represent the analogous results from the thru- and drop-port at 1558.7 nm (TM_2) resonance. The red traces in (b) and (d) stand for the total power including both pump and comb lines.

As a further test, we investigated a resonance belonging to the TM_2 family at ≈ 1551.5 nm with a relatively low Q ($\approx 6.5 \times 10^5$). For this resonance no comb was generated at up to 430 mW input power, the highest power tested. The pump power emerging from the drop-port was approximately linear with input power, with no sign of saturation. This supports our interpretation that the drop-port data of Fig. 4 provide evidence of parametric gain saturation directly connected to Kerr comb formation.

From Fig. 4 we also observe that the output power from the comb obtained by pumping at TM_2 is substantially higher than that for the comb obtained by pumping at TM_1 . Furthermore, in both cases the output power in the comb is relatively small compared to the input power. We may understand these trends, at least in part, from the linear transmission spectra and coupling parameters. For the TM_1 resonance, the total drop-port output power at the highest pump level is 9.6 mW, quite close to the 12 mW value obtained from the product of the pump power (430 mW) and the linear drop-port transmission ($T_{drop} = 0.028$). A similar estimate for the total drop-port power for the TM_2 resonance, using 680 mW pump power and $T_{drop} = 0.142$, yields 97 mW, higher than but within a factor of two of the observed value (55 mW).

In addition to linear behavior, a saturation behavior is evident for the comb and total (comb plus pump) drop-port power data in both resonances, but most notably in Fig. 4(d). One possible explanation is that the fraction of pump power actually coupled into the microresonator is reduced above comb generation threshold. Under linear operation and at resonance, the pump power enhancement in the microring is given by [compare Eq. (2)]:

$$\frac{P_{\mu ring}}{P_{in}} = \frac{4\kappa_e^2}{(\kappa_d^2 + \kappa_p^2 + \kappa_e^2)} \quad (3)$$

where $P_{\mu ring}$ and P_{in} are the resonantly enhanced pump power in the microresonator and the input power, respectively. Above threshold, power is transferred out of the internal pump field and into the comb. This effectively increases the value of κ_p^2 that should be used in Eq. (3). For an under-coupled resonator, as in the experiments here, this means that increasing power transfer into the comb decreases the total power fraction coupled into the resonator. As a result the slope efficiency of the total (comb plus pump) power emerging from the drop-port is also reduced. Equivalently, we can also observe that gain clamping affects the ratio of the pump field inside the microresonator to the pump field in the input guide, which in turn affects the interference condition governing the power transmitted to the thru-port. For the case of under-coupling, this increases the fraction of the input power transmitted to the thru-port and decreases the fraction coupled into the microresonator and available for comb generation.

4. Time-domain characterization with drop-port geometry

The drop-port geometry also provides advantages for time-domain studies. Previous time-domain investigations characterized the comb at the thru-port [9, 10, 13–16]. In [9, 10, 13] line-by-line pulse shaping was used to compress the comb into a bandwidth-limited pulse train and demonstrate high coherence. Here the pulse shaper compensated the phase of the total field, including both the comb field as generated and the dispersion of the subsequent fiber link that relayed the comb to the measurement apparatus. However, because the dispersion of the fiber link was not characterized, no attempt was made to separate the initially generated comb waveform from subsequent dispersive reshaping. Subsequent investigations incorporated dispersion compensation into the fiber link and reported generation of ultrashort pulses directly in the microresonator [14, 15]. Note that [14, 15] both consider devices with anomalous group velocity dispersion. In all of these time-domain studies, suppression of the very strong pump line present at the thru-port, which would otherwise contribute a strong background field, was necessary. Reference [15] used a spectral filter to select a region of the comb away from the pump region for characterization, while in [9, 10, 13, 14] a pulse shaper or fiber-Bragg grating was used to attenuate the pump line. Here we upgrade our setup by dispersion compensating the fiber link and utilize the drop-port geometry to obtain a smooth spectrum directly from the microring. This enables time-domain characterization of the comb without the need for any intentional amplitude filtering. We report observation of ultrashort pulse generation directly from the microring, with low background and without filtering of the pump.

The autocorrelation trace of the comb generated from the TM_1 resonance, corresponding to the drop-port spectrum in Fig. 3(a), is plotted as the blue trace in Fig. 5. A pulse-like intensity autocorrelation is directly obtained. The measured pulse train has a period of 1.45 ps, corresponding to a 689 GHz repetition rate, consistent with the comb spacing of 5.52 nm (3 FSRs). The green trace in Fig. 5 shows the autocorrelation trace calculated on the basis of the optical spectrum after the EDFA and assuming flat spectral phase. The experimental and calculated traces are close but are not perfectly matched; experimental and simulated autocorrelations have widths of 526 fs and 423 fs, respectively (full-width half-maximum). One possible reason is that the pulses are short enough that residual higher-order dispersion in the fiber link causes some broadening. Another possibility is that for this case the field internal to the microring is itself slightly broadened compared to the bandwidth-limit.

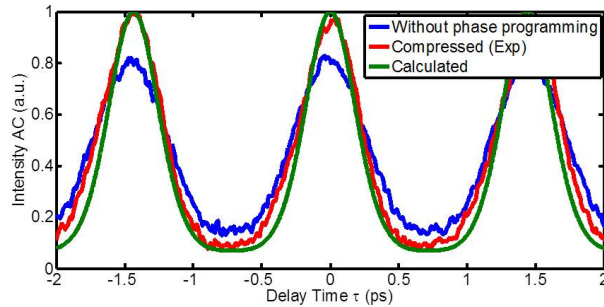


Fig. 5. Autocorrelation traces corresponding to the drop-port spectrum in Fig. 3(a). The green trace shows the intensity autocorrelation trace calculated by taking the optical spectrum and assuming flat spectral phase, while the blue and red traces show the measured autocorrelation traces before and after the line-by-line phase compensation.

For this particular comb, we also performed experiments in which a programmable pulse shaper is placed before the EDFA. The pulse shaper was used to fine tune the spectral phase, as in [9, 13], but without modifying the shape of the optical power spectrum. The measured autocorrelation trace after fine tuning the phase (red trace) is in close agreement with the calculation. This indicates a high level of coherence, in accord with previous studies of combs generated directly at multiple FSR spacing, e.g [9].

We obtained more dramatic examples of a pulse-like intensity autocorrelation by pumping different resonances of the same TM_1 mode family. Note that no pulse shaping is performed in these experiments. Figure 6(a) and 6(b) show the optical spectra at 1 W pump power around 1560.4 nm, measured respectively (a) directly after the drop-port and (b) after the EDFA. The comb is formed directly with single free spectral range (FSR) line spacing, and the RF intensity noise of the generated comb (not shown here) is low, close to the background noise of the electrical spectrum analyzer (ESA). Again, a smooth spectrum is obtained, without the need for spectral filtering or pump attenuation after the microresonator. The dramatic difference of the spectra [including different comb spacings, see Figs. 3(a) and 6(a)], obtained upon shifting the pump by only one free spectral range, is not unusual according to our experience with comb generation in normal dispersion cavities, e.g [9]. Such behavior has also been observed in [27] and has been explained on the basis of interaction with different mode families, which can produce strong local disturbances in the dispersion. The measured autocorrelation trace, plotted as the blue line in Fig. 6(c), matches well with the trace simulated assuming flat spectral phase (green trace). The pulses have a period of 4.35 ps, corresponding to a 230 GHz repetition rate, consistent with the 1.84 nm comb spacing, with measured autocorrelation width ≈ 698 fs FWHM. Between peaks the autocorrelation reaches a minimum value equal to approximately 2% of the peak autocorrelation, providing direct evidence of low background intensity. A similar pulse-like intensity autocorrelation is observed at 700 mW pump power for pumping around 1562.2 nm. Figures 6(d) and 6(e) show the corresponding optical spectrum and autocorrelation results, respectively. Here the autocorrelation width is ≈ 1.1 ps FWHM, and the autocorrelation minimum is 4% of the peak value. In both cases, the close agreement apparent between experiment and simulation suggests passively mode-locked operation leading to nearly bandwidth-limited pulses internal to the microresonator.

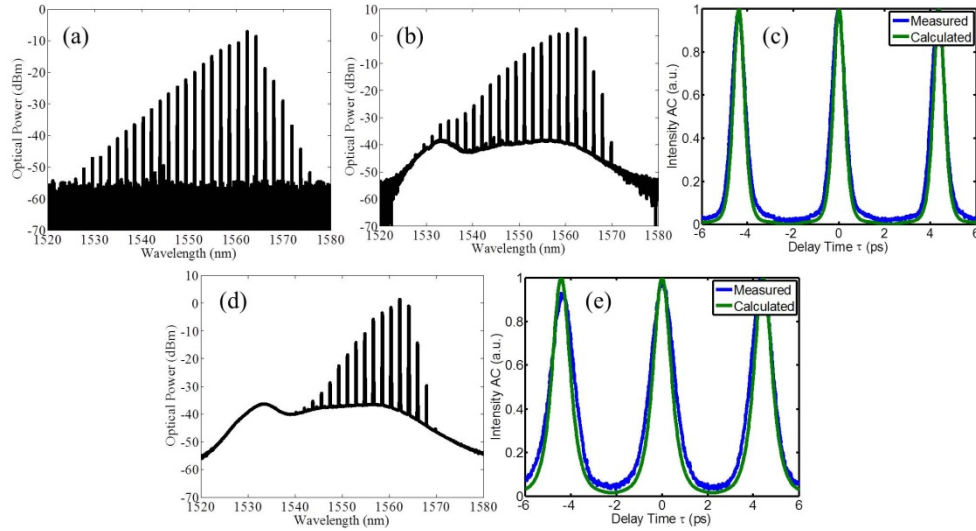


Fig. 6. (a) Optical spectrum measured from the drop-port with input power of 1 W at around 1560.4 nm. (b) The corresponding optical spectrum after the EDFA. (c) Measured (blue) and calculated (green) autocorrelation traces. (d)-(e) The optical spectrum after the EDFA and the autocorrelation measurement with input power of 700 mW at around 1562.2 nm.

It is worth reiterating that previous studies reporting passive mode-locking of the comb consistent with soliton-pulse formation were performed with devices in the anomalous dispersion regime [14, 15]. Our results provide evidence for passively mode-locked pulse generation, with low intracavity background field, for microresonators in the normal dispersion regime. Although a theoretical explanation is not fully available at this point, we may speculate – as does [15] – that nonlinear amplitude modulation may play a role, especially with respect to our observation of low background field.

5. Conclusion

We have compared comb spectra generated at the thru- and drop-ports of a silicon nitride microresonator in the normal dispersion regime. Drop-port measurements provide the ability to directly probe the field in the microresonator without the strong copropagating pump common to the usual thru-port geometry. Although otherwise similar to spectra observed at the thru-port, the drop-port spectra differ in that the intensity of the pump line is comparable to that of neighboring comb lines. Furthermore, most of the ASE background present at the input and transmitted to the thru-port is filtered out at the drop-port. Our data also provide information on saturation of the pump power and of the Kerr comb itself. The smooth spectra obtained from the drop waveguide are beneficial for the time-domain studies, allowing waveform characterization without the need to suppress the potentially large background associated with the strong residual pump in the thru-port geometry. By performing autocorrelation measurements in a spectral region spanning the pump line, we have observed passively mode-locked pulses with inherently low background in the normal dispersion microcavity.

Acknowledgment

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