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# Modelling Brillouin activated microcombs in multi-layered silicon nitride waveguides

*(Student paper)*

**Yvan Klaver[1*], Kaixuan Ye[1], Roel Botter[1] and David Marpaung[1]**

[1]Nonlinear Nanophotonics, MESA+ Institute of Nanotechnology, Department for Science and Technology, Applied Nanophotonics, University of Twente, 7522 NB Enschede, The Netherlands

[*] y.klaver@utwente.nl

**We investigate a numerical model to simulate the optical frequency comb generation in Kerr and Brillouin active resonators with gain parameters in the same order of magnitude. We show that either a backward or forward comb can be generated directly on a Brillouin laser or a cascaded Brillouin lasing mode respectively for a multi-layered silicon nitride waveguide structure.**

***Keywords***: *Microring resonators, Stimulated Brillouin scattering, Kerr nonlinearity, Optical frequency comb*

## INTRODUCTION

Optical frequency combs are a widely studied optical source in which a repetition of the optical signal is coupled to the frequency domain and are used in spectroscopy, metrology, and communications [1]. Particularly for high repetition rate applications such as communication, microcombs also known as Kerr frequency combs have been extensively studied [2]. In this field a high-Q microcavity is pumped with a continuous wave laser to obtain a pulsed output due to the Kerr effect in the microcavity. One of the interests in these microcombs is to have them highly coherent in both RF and optical domain, where the latter is given by the optical linewidth of the comb lines. When stabilised the well-defined frequencies could reduce errors when the comb is used as a grid of data carriers.

A way to achieve high spectral purity in microcombs has been shown in earlier research where they activate microcombs via a Brillouin laser in the same cavity acting as a photonic flywheel [3,4]. A Brillouin laser narrows the linewidth of the pump laser [5] and transfers this high coherence as a starting point to the microcomb. A following step for these Brillouin activated microcombs is to perform this in planar technologies. However, in planar technologies the mode volumes are generally much smaller than in the given examples, this means the Kerr effect is significant and we cannot assume Brillouin scattering dominates until enough power mixes in the Kerr process.

In this paper we will theoretically investigate this region where the Brillouin and Kerr strength are relatively close by use of waveguide properties known for different platforms. Particularly we will investigate multilayer silicon nitride waveguides which exhibit Brillouin scattering with high confinement [6]. For this we will show that microcomb generation via Brillouin lasing is still possible in highly confined waveguides under the conditions that selective inhibition of microcombs followed by inhibition of cascaded Brillouin lasing. Additionally, we show the cascaded Brillouin lasing can activate combs in the forward direction.

## METHODS

For the model we have a set of two Lugiato-Lefever equations for the microcombs with cross-phase modulation for the counter propagating waves [7], however we transform this in modal components and couple these via acoustic waves [8]. This results in a large set of coupled mode equations for the forward and backward direction in the resonator described for each longitudinal mode as:

$$\frac{dE_\mu^F}{dt} = -\left(\frac{\Delta\omega_L}{2} + i\delta\omega_P\right)E_\mu^F + iD_{int}(\mu)E_\mu^F - i\gamma v_g\mathcal{F}\left[E_\tau^F\left(|E_\tau^F|^2 + 2\langle|E_\tau^B|^2\rangle\right)\right]_{\tau\to\mu} - ig^*E_{\mu+m}^B B_\mu^{B^*} - igE_{\mu-m}^B B_{\mu-m}^F + \delta_{\mu,0}\sqrt{FSR_0\Delta\omega_{ext}}E_{in} + \eta_\mu \quad (1)$$

$$\frac{dE_\mu^B}{dt} = -\left(\frac{\Delta\omega_L}{2} + i\delta\omega_P\right)E_\mu^B + iD_{int}(\mu)E_\mu^B - i\gamma v_g\mathcal{F}\left[E_\tau^B\left(|E_\tau^B|^2 + 2\langle|E_\tau^F|^2\rangle\right)\right]_{\tau\to\mu} - ig^*E_{\mu+m}^F B_\mu^{F^*} - igE_{\mu-m}^F B_{\mu-m}^B + \eta_\mu \quad (2)$$

$$\frac{dB_\mu^F}{dt} = -\left(\frac{\Gamma}{2} + i\delta\omega_B\right)B_\mu^F - i\frac{g^*}{FSR_0\hbar\omega_\mu}E_{\mu+m}^F E_\mu^{B^*} + \xi_\mu \quad (3)$$

$$\frac{dB_\mu^B}{dt} = -\left(\frac{\Gamma}{2} + i\delta\omega_B\right)B_\mu^B - i\frac{g^*}{FSR_0\hbar\omega_\mu}E_{\mu+m}^B E_\mu^{F^*} + \xi_\mu \quad (4)$$

For this we have the optical field $E_\mu^F$ and $E_\mu^B$ for mode $\mu$ in the forward and backward direction respectively. Further we have for the optical equations we have: the optical decay rate $\Delta\omega_L$, pump detuning $\delta\omega_P$, integrated cavity dispersion $D_{int}(\mu)$, nonlinear parameter $\gamma$, group velocity $v_g$, opto-acoustic coupling $g$, the free spectral range $FSR_0$, coupling rate $\Delta\omega_{ext}$ and Langevin noise term $\eta_\mu$. For the acoustic equations we have $B_\mu^F$ the photon number amplitude for mode $\mu$ in the forward and backward direction respectively and: the acoustic decay rate $\Gamma$, acoustic detuning $\delta\omega_B = 2\pi FSR_0 - \Omega_{SBS}$, frequency of the photons $\omega_\mu$ and the Langevin noise for the acoustic mode $\xi_\mu$.

The optical modes in this simulation uses a discrete Fourier transform $\mathcal{F}[\dots]_{\tau\rightarrow\mu}$to express the Kerr nonlinearity, which is characterised in time domain. Additionally, the cross-phase modulation is given by the term $2\langle|E_\tau^x|^2\rangle$ where the brackets express averaging.

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|---|---|---|---|
| Brillouin gain | $g_b$ | 0.58 | $m^{-1}W^{-1}$ |
| Nonlinear parameter (Kerr gain) | $\gamma$ | 0.18 | $m^{-1}W^{-1}$ |
| Stimulated Brillouin scattering frequency shift | $\Omega_{SBS}$ | 13.18 | GHz |
| Acoustic decay rate | $\Gamma$ | 92 | MHz |
| Group velocity dispersion | $\beta_2$ | 571 | $ps^2km^{-1}$ |

*Table. 1. Parameters used for simulations of 4 µm wide multi-layered silicon nitride waveguides*

We simulate this for the case of multilayer silicon nitride given by [6] and use the simulated values for a waveguide with a width of 4 µm as given in Table 1. In the simulations we vary the pump powers and the acoustic detuning ($\delta\omega_B$) and assume a loss of 5 dB/m with critical coupling ($\eta = \frac{\Delta\omega_{ext}}{\Delta\omega_L} = 0.5$). The simulations are performed by slowly tuning the pump frequency over the resonance whilst running an ODE solver (MATLAB ODE45).

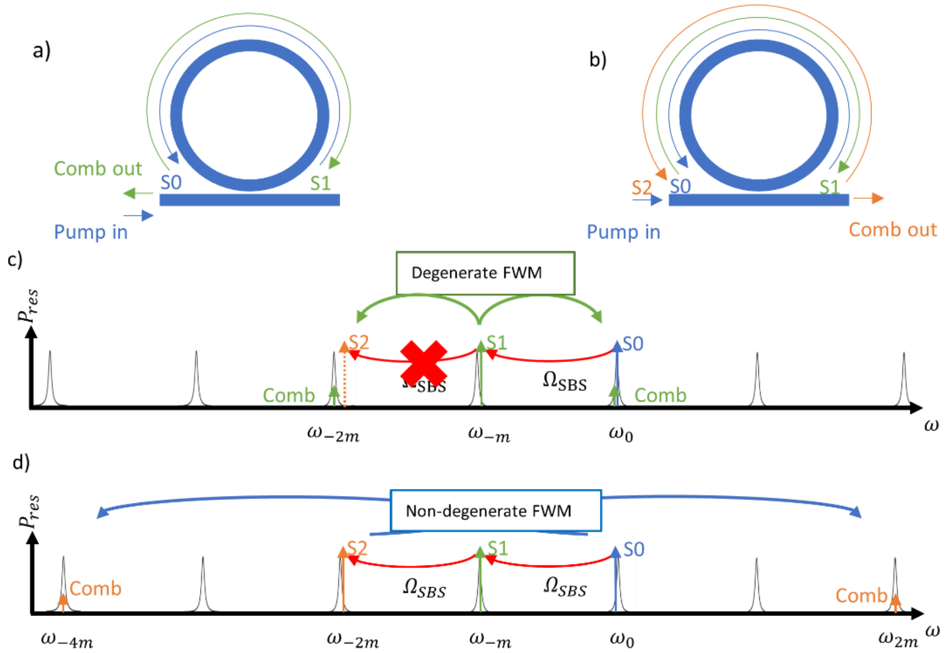


*Fig. 1. Development of a a) backward comb or b) forward comb. With the spectral components given in figure c) and d) respectively matched to the propagation directions of a) and b). In c) the S1 lasing mode starts from the pump (S0) but cannot cascade before mixing into a comb via degenerate four-wave mixing (FWM). Whereas in d) the S1 lasing mode cascades into the S2 lasing modes which via non-degenerate FWM can develop a forward comb that is stable.*

## RESULTS

In the results we find two main comb operations in the resonator: a comb in the backwards direction or a comb in the forwards direction. The formation of these categories is illustrated in Figure 1. Here the comb, either forms in the backwards direction as cascaded lasing does not happen due to the larger detuning or forms in the forwards direction as cascaded lasing can take place. Note also that the forward comb generation will have a linespacing twice the Brillouin shift instead of just one FSR as is the case for the backward comb.

The different operating regimes are shown in Figure 2, where only the acoustic detuning $\delta\omega_B = 2\pi FSR_0 - \Omega_{\text{SBS}}$ is changed to switch from backward comb generation to forward comb generation. In these figures we also have the comb line spacing in the backwards direction as one FSR whereas the forwards direction has two FSR spacing as the Brillouin shift is nearly matched to the FSR. For different acoustic detuning and pump powers it was observed that forward combs with one FSR existed, but these were not stable and disappeared quickly.

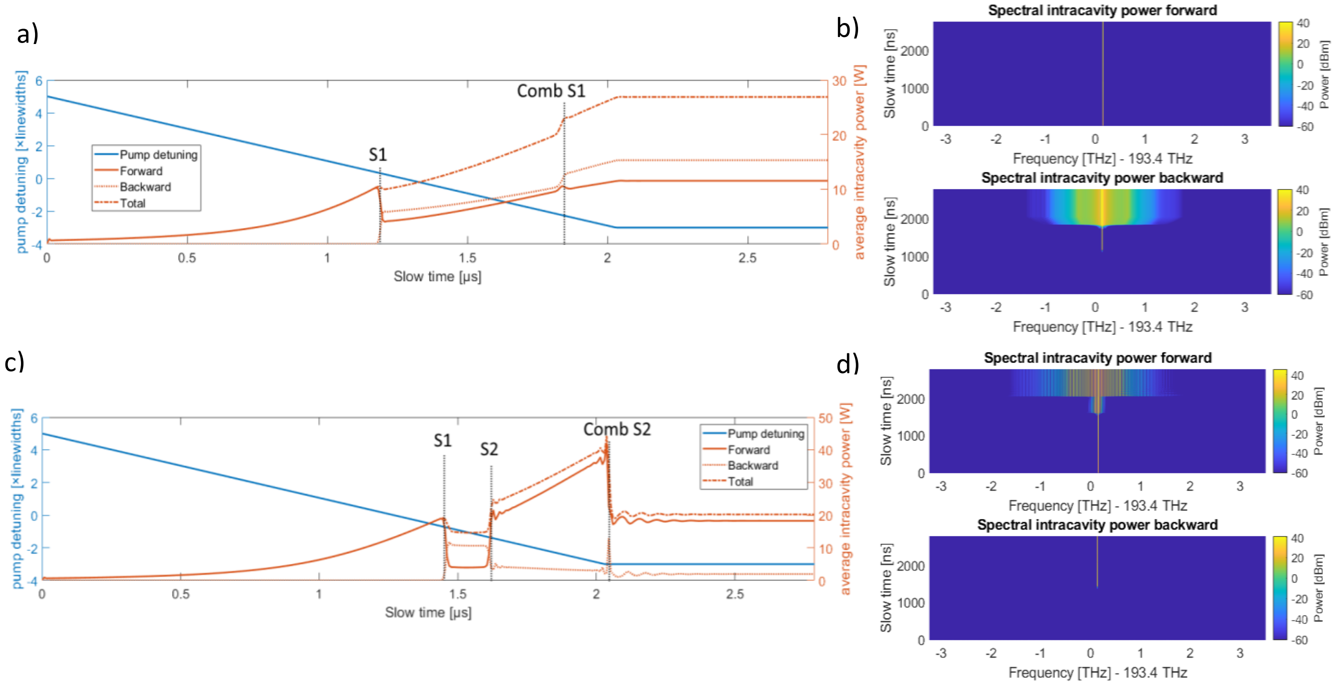


*Fig. 2. Example operation of a b) backward comb via Brillouin lasing and d) forward comb via cascaded Brillouin lasing. Where we have corresponding figures showing the pump sweep and intracavity power in the different directions for a) the backward comb and c) the forward comb. In b) and d) the power per mode is given over the same time axis for the forward (top) and backward (bottom) direction. Between these results only the acoustic detuning is changed between b) $\delta\omega_B = 2\pi\times(100\ \text{MHz})$ and d) $\delta\omega_B = 2\pi\times(25\ \text{MHz})$*

The transition between forward and backward comb generation is found to be in a small region around 50 MHz depending on the pump power. A narrower waveguide (1.2 µm) which exhibits a relatively larger Kerr but smaller Brillouin nonlinearity had a similar transition but with a narrower region of backward comb generation as microcomb generation starts with less power whilst the cascaded Brillouin lasing threshold increased.

**DISCUSSION**

Currently we have simulated the Kerr and Brillouin interactions in high-Q resonators and shown that comb generation via Brillouin lasing is possible both in forward and backward direction. For the next step, expansion of the parameter space by including more platforms that observe Brillouin scattering would give more insight in changing the ratio of Brillouin to Kerr nonlinear strength. Additionally, noise dynamics would be an important aspect to simulate to see if the Brillouin lasing in this context still filters high frequency noise of the pump and transfers this to the comb lines.

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