Tapered Microresonator design for increasing microcombs' bandwidth

Zhen Tao
Wuhan National Laboratory for Optoelectronics & School of Optical and Electronic Information
Huazhong University of Science and Technology
Wuhan, China

Liao Chen*
Wuhan National Laboratory for Optoelectronics & School of Optical and Electronic Information
Huazhong University of Science and Technology
Wuhan, China
liaochenchina@hust.edu.cn

Yufan Du
Wuhan National Laboratory for Optoelectronics & School of Optical and Electronic Information
Huazhong University of Science and Technology
Wuhan, China

Zichun Liao
Wuhan National Laboratory for Optoelectronics & School of Optical and Electronic Information
Huazhong University of Science and Technology
Wuhan, China

Chi Zhang
Wuhan National Laboratory for Optoelectronics & School of Optical and Electronic Information
Huazhong University of Science and Technology
Wuhan, China

Xinliang Zhang
Wuhan National Laboratory for Optoelectronics & School of Optical and Electronic Information
Huazhong University of Science and Technology
Wuhan, China

***Abstract*—The microresonator is optimized by tapered design with two waveguides of different widths. Through balancing the dispersion and loss, the bandwidth of microcombs is improved by 61.2% compared with the traditional one.**

Keywords—Frequency combs, dispersion management, microresonator design

I. Introduction

Kerr frequency combs (microcombs) based on microresonators with advantages of high repetition rate, compact size and broad bandwidth have been widely applied in dual-comb spectroscopy, atomic clocks, optical coherent communications and so on[1]. In many applications, the broader bandwidth of microcombs is a critical parameter and mainly determined by the overall dispersion of the microresonator. Many microresonator's dispersion management methods have been proposed and investigated such as the cross section design of waveguides[2], the overall design of the microresonator [3], the waveguide with a carefully designed slot[4]. Recently, a tapered microresonator with wide waveguide and narrow waveguide are proposed to overcome the trade-off between loss and dispersion and demonstrated a high Q of 8.0 million[5]. However, there is no further investigation to discuss the influence on the spectrum bandwidth of the microcombs. Here, we carefully design a tapered microresonator which consisted of the waveguides of different widths (one wide and one narrow) to increase the bandwidth of microcombs. The normal dispersion of wide waveguide can flat the phase match curve of the narrow waveguide. Therefore, the bandwidth of tapered microresonator is greatly extended compared with the normal resonator of only narrow waveguide.

II. Principle

LLE equation model is used to describe the generation of microcombs [6]:

$$t_R\frac{\partial E}{\partial t}=[-\alpha-i\delta_0+iL\sum_{k\geq 2}\frac{\beta_k}{k!}(i\frac{\partial}{\partial\tau})^k+i\gamma L|E|^2]E+\sqrt{\theta}E_{in} \tag{1}$$

Where t_R is the roundship time, δ_0 is the detuning of the microresonator, α is the total cavity losses, γ is the nonlinear coefficient, β_k is the dispersion coefficient of each order in the microresonator, and E_{in} is the pump driving field. The generation of microcombs is very sensitive to the group velocity dispersion of the cavity. Generally speaking, if the microresonator can be kept in a state of anomalous dispersion (i.e. β_2 <0), it is very favorable for the generation of microcomb[4]. Skillful geometric designs are used to obtain a relatively flat anomalous dispersion curve for increasing the microcombs' bandwidth, but most of these schemes are complex and add additional loss. We found that the wide waveguide can not only bring lower loss because of less contact between the side wall and the light field, but also has relatively flat dispersion curve in the positive dispersion region for the result of material dispersion. Therefore, the width and length of the wide waveguide can be carefully designed to compensate the anomalous dispersion of the narrow waveguide. In this way, the overall dispersion curve of the cavity can be located in the anomalous dispersion region and relatively flat to generate the microcombs with broader bandwidth. As an proof of concepts，different from the traditional microresonator with only one width shown in Fig.1(a), we tried to designed a tapered microresonator which consisted of the waveguides of two different widths ,whose structure is shown in Fig.1(b). The new microresonator is composed of a wide waveguide with width W_1 and a narrow waveguide with width W_2. Since waveguides with different widths have different dispersion curves, the dispersion curve of the whole new microresonator is jointly determined by the dispersion curve of width structure W_1 and W_2. To simplify the simulation, the lengths of the two waveguides are both set to half the length of the microcavity, and the taper structure in the middle is ignored due to its small size relative to the microcavity.

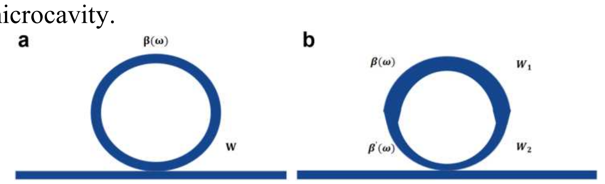

Fig.1. (a) (b) Structure diagram of the traditional and tapered microresonator

III. SIMULATE AND DISCUSSION

In the simulation, the microresonator's height is set to 800nm, referring to the Ligentec company. The length of the microresonator is designed to be 711.3μm, the FSR of the corresponding microcomb is 100GHz.We used COMSOL software to simulate the dispersion curve of the microresonator. The group velocity dispersion D is used to describe the dispersion in the microresonator, where $D = -\frac{2\pi c}{\lambda^2}\beta_2$ .The width of the microresonator was first determined at 1100nm. The dispersion curve is the black line shown in Fig.2(a). The zero dispersion wavelength is around 1550nm. However, its dispersion change reaches 935ps/(km*nm) in the wavelength range of 1500nm, indicating that the dispersion curve is not flat. When the width is further increased to 5500nm, the dispersion curve is the blue line shown in Fig.2(a), whose zero dispersion wavelength also appears near 1550nm. Besides, the dispersion curve is relatively flatter all in the normal dispersion region compared with the former with. Therefore, we choose W=1100nm as the narrow waveguide and W=5500nm as the wide waveguide, and set the wavelength of pump as 1550nm. The final tapered microresonator's dispersion curve is the red line shown in Fig.2(a). Compared with the 1100nm microresonator, it can be seen that the dispersion curve of the designed structure is significantly flatter, and its dispersion change in the wavelength range of 1500nm is 510ps/(km*nm).

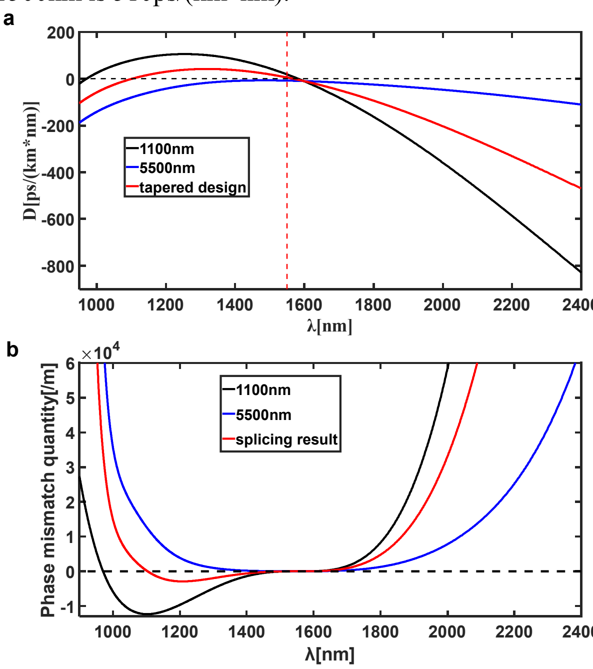

Fig.2.(a) dispersion curves of 1100nm microresonator(black), 5500nm microresonator (blue),tapered microresonator (red) respectively.(b) phase mismatch curves of 1100nm microresonator (black), 5500nm microresonator (blue),tapered microre- sonator (red) respectively.

The nonlinear coefficients of 1100nmwaveguide and 5500nm waveguide by COMSOL software are 1.6466 $W^{-1}m^{-1}$ and 0.3910 $W^{-1}m^{-1}$, respectively. The phase mismatch curve can be used to show the nonlinear effect more accurately(Fig.2(b)), which is determined by each order of dispersion. When i-th order dispersion in the microresonator is considered, the calculation formula of phase mismatch is as follows [7] :

$$\Delta\delta = \sum_{k=2}^{i} \beta_k (\omega-\omega_0)^k / k! - \gamma_0 P_s / 2 \tag{2}$$

where ω_0 is the pump frequency, γ_0 is the nonlinear coefficient at the pump position, and P_s is the peak power of the soliton. Just like the dispersion curve, the phase mismatch curve of tapered design (red line) shown in Fig.2(b) is flatter than the phase mismatch curve of 1100nm microresonator (black line), indicating that it is easier to generate microcombs with a broader bandwidth.

The simulation results of soliton microcombs based on the LLE model are shown in Fig.3. The spectrum is normalized to the highest value of the soliton envelope. The single soliton microcomb of 1100nm microresonator is shown in Fig.3(a). It can be seen that the bandwidth range is 521nm over -60dB threshold defined as the effective range. The inconsistency between the pump and microcombs' peak position is due to the effect of the Raman red shift in the simulation. It forms a stable single soliton in the time domain. The single soliton microcomb of the tapered microresonator is shown in Fig.3(b). The bandwidth range is 840nm over -60dB threshold .The uneven of the microcombs may be caused by the dispersion jitter of the tapered design. In order to make a clearer comparison, we put the envelope of the two microcombs together shown in Fig.3(c), It can be seen the microcombs' bandwidth brought by the tapered design increases by 61.2% based on -60dB.

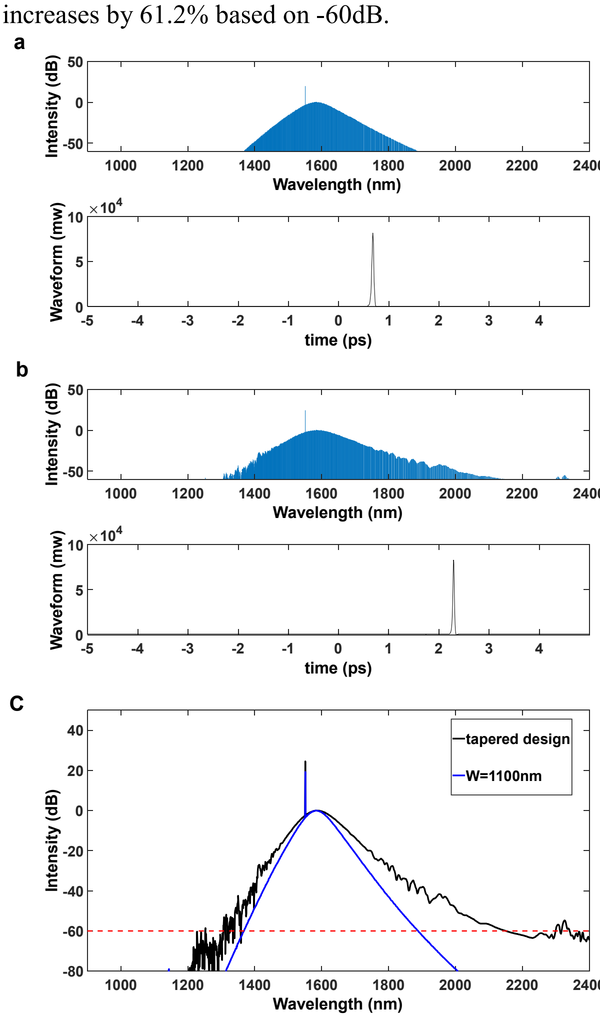

Fig.3.(a) single soliton microcombs of 1100nm resonator.(b) single soliton microcombs of tapered design.(c)Comparison of microcombs between 1100nm and tapered design.

IV. CONCLUSION

A tapered design of two waveguides with different widths is used to broaden the bandwidth of the microcombs. The designed microresonator is composed of two waveguides with a height of 800nm and widths of 1100nm and 5500nm respectively. According to the simulation results, the phase mismatch of the new microresonator is flatter than the traditional microresonator with the width of 1100nm, and the bandwidth of soliton microcombs can be improved by 61.2% based on -60dB. This work proves that the tapered design can improve the bandwidth of microcombs and provides a new idea and method for broadening the performance of microcombs in the future.

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