Raman Amplification with ring resonators

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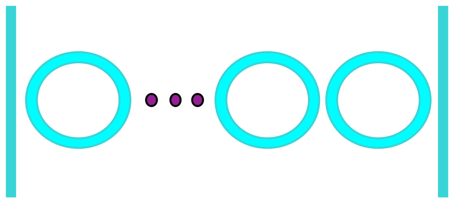
Abstract

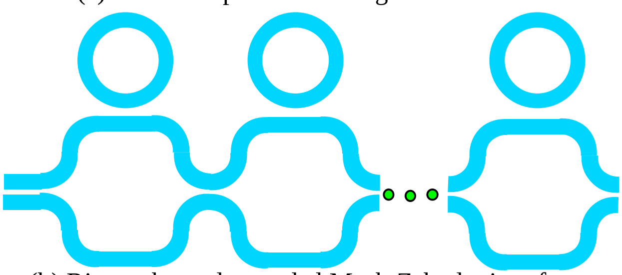
We study Raman amplification in two ring-resonator structures: direct-coupled ring resonator lattice and ring-based Mach-Zehnder lattice. Raman amplification is determined by pump power, signal power, interaction length, and nonlinear Kerr index. Ring-resonator filters can be designed with high Q factor, which can cause relatively high Raman amplification efficiency with low pump power, low nonlinear Kerr index or short interaction length. Therefore, these filters can be used for on-chip amplification. The cascade micro-ring resonator (CMRR) structure had been discussed in [1]. Raman amplification in direct-coupled ring resonators and ring-based Mach-Zehnder interferometers are discussed in this paper. Simulation results prove that they can provide significant amplification with limited propagating area.

Recently, there has been considerable activity in amplification schemes based upon stimulated Raman scattering (SRS). [2~5] Even though there are some materials with relatively large Raman gain coefficients (as compared to silica, for example), the efficiency of on-chip Raman amplification is low compared to optical fiber due in part to the short path lengths involved. Therefore, we use micro-ring resonator slow-light structures as means to increase SRS conversion efficiency.

Figure 1 shows two ring-resonator structures. Figure 1a is the direct-coupled microring resonator (DMRR) lattice structure. It consists of an input waveguide, an output waveguide, and a sequence of rings. Power at the resonant frequency is transferred from the input waveguide to the rings, and then to the output waveguide. All the rings in this structure have the same diameter. Figure1b is a ring-enhanced cascaded Mach-Zehnder interferometer (RECMZI). It is consist of Mach-Zehnder interferometer (MZI) lattice. Each MZI has a micro-ring resonator in one of its arms.



(a) Direct-coupled micro-ring-resonator



(b) Ring-enhanced cascaded Mach-Zehnder interferometer

Figure 1 Ring-resonator structures

The two structures are designed by optimization methods [8]. Then they are simulated by a nonlinear propagation method. The optimization method doesn't include SRS, while the nonlinear method does.

To describe SRS within the ring, we use the following coupled nonlinear differential equations for the pump and signal waves

$$\frac{dE_p}{dz} = -\frac{\alpha}{2}E_p + ik_{fp}n_2(1+iK)(|E_p|^2 + 2|E_s|^2)E_p - k_{fp}n_2R_p|E_s|^2E_p$$

$$\frac{dE_s}{dz} = -\frac{\alpha}{2}E_s + ik_{fs}n_2(1+iK)(|E_s|^2 + 2|E_p|^2)E_s - k_{fs}n_2R_s|Ep|^2E_s$$

where n_2 is the nonlinear Kerr index, $K=\beta_2/2k_fn_2$ is the normalized two-photon absorption coefficient, β_2 is the two-photon absorption coefficient, $R = g_R/2k_fn_2$ is the normalized Raman amplification coefficient, g_R is the Raman gain coefficient. The equations are used to relate the fields at the input (i.e. $E_p(0)$ and $E_s(0)$) of a resonator to the fields at the output (i.e. $E_p(L)$ and $E_s(L)$). This calculation is iterated within each ring (taking into account the coupling of light between the ring and the bus waveguide) sequentially. [7]

The transfer function method was developed to analyze DMRR structures [8]. Figure 2 shows the mechanism of the method. This method calculates the input from the output directly. Pump depletion caused by Raman amplification will affect the power distribution in steady state. Therefore, we cannot use the transfer function method to calculate Raman amplification - we have to use the propagation method, which simulates the propagation of the electric field in the waveguides. The program will keep iterating until the power distribution reaches steady state. Figure 3 shows the amplification of DMRR designed in reference. [9] The structure is formed of 9 ring resonators. The guiding material is a general material with a refractive index of 2 and a Raman factor one tenth that of silicon. The structure has a free spectral range of 3000GHz and a bandwidth of 100GHz. Figure 3 shows the amplification within the passband with different value of n_2*Ip. Figure 3A is the gain profile when the value of n_2*Ip is small (<5e-7). Figure 3B shows the amplification when n_2*Ip is greater.

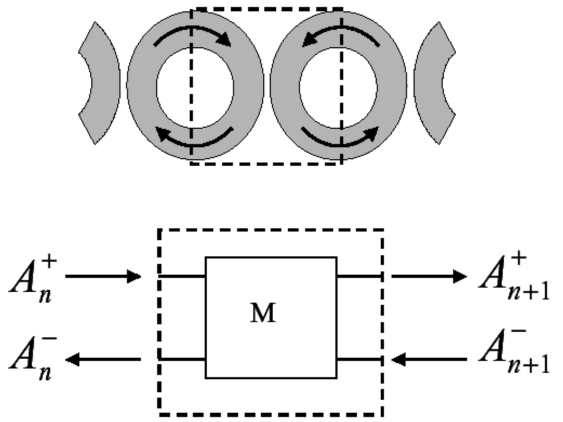
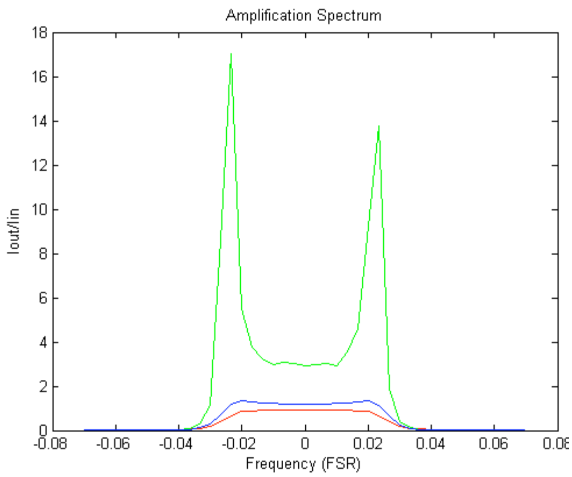
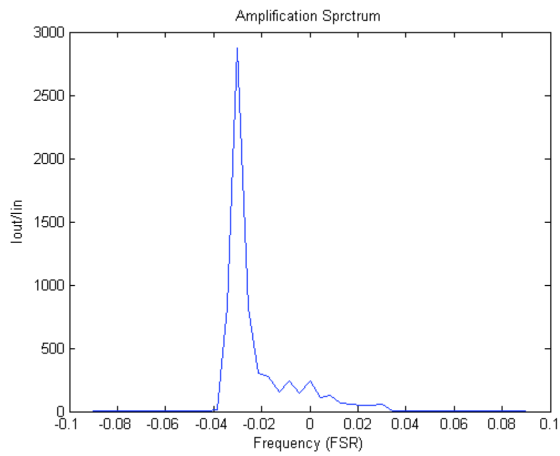


Figure 2 Transfer function method



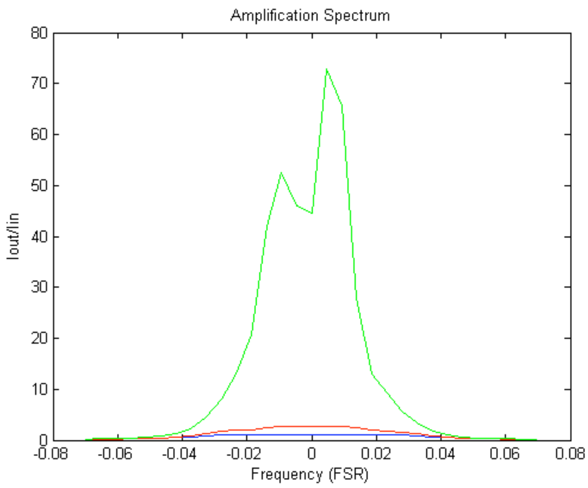
(a) when n_2*Ip = 0, 1e-7, 4e-7



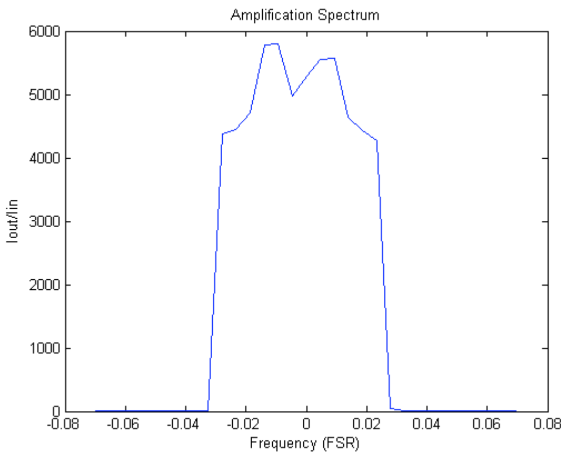
(b) n_2*Ip = 5e-7

Figure 3 Gain spectrum of DMRR

The transfer function method has also been developed to analyze RECMZI. But with the same problem as DMRR, we cannot use this method to simulate Raman amplification. However, we can still use it to verify the validation of the propagation method. Figure 4 shows the amplification in the passband with different value of n_2*Ip. Figure 4A is the gain spectrum when the value of n_2*Ip is small (<2e-7). Figure 4B shows the amplification when n_2*Ip is greater.



(a) when n_2*Ip = 0, 1e-7, 2e-7



(b) when n_2*Ip = 2.5e-7

Figure 4 Gain spectrum of RECMZI

Amplification in the passband has been shown for the two structures. The shape of the amplification spectrum of DMRR is not very regular. But that of RECMZI has a much better shape. Also the amplification factor of RECMZI can get into the thousand range with a value of n_2*Ip as low as 2.5e-7. From this paper, we can see that ring-base filters can generate on-chip amplification up to several thousand with SRS.

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