Negative curvature fibers for gas-filled fiber lasers

Chengli Wei[a], Francois Chenard[b], Curtis R. Menyuk[c], Jonathan Hu*[d]

[a]Department of Computer Science, Engineering and Physics, University of Mary Hardin-Baylor, 900 College Street, Belton, TX 76513, USA
[b]IRflex Corporation, 300 Ringgold Industrial Parkway, Danville, VA 24540, USA
[c]Department of Computer Science and Electrical Engineering, University of Maryland, 5200 Westland Blvd., Baltimore, MD 21227, USA
[d]Department of Electrical and Computer Engineering, Baylor University, One Bear Place #97356, Waco, TX 76798, USA

Abstract

We find optimal structure for chalcogenide negative curvature fibers with different thicknesses and gaps between cladding tubes to yield low transmission loss at wavelengths of 1.5 μm and 4.5 μm simultaneously for gas-filled fiber lasers.

Keywords: negative curvature fiber, fiber laser, simulation, chalcogenide glass, gas laser

*Jonathan_hu@baylor.edu; phone 1 254 710-1853

I Introduction

Mid-infrared lasers are widely used in sensing, medical, and defense applications [1]. The invention of hollow-core fibers and their ability to host gases for long interaction lengths and micrometer-scale mode areas made possible the use of new gas-filled hollow-core fiber lasers at mid-infrared wavelengths [2]. Using a pump at 1.5 μm, emission at around 4.5 μm has been realized in hollow-core fibers filled with H_2 or N_2O gases [3–5]. Recently negative curvature fibers with a broad bandwidth and low loss have drawn much attention because it is possible to fill the fibers with gas or liquid [6–9]. It has been shown that negative curvature fibers that are made with chalcogenide glass have lower loss than negative curvature fibers made with silica glass if the wavelength is longer than 4.5 μm [10]. In this paper, we computationally study the leakage loss in the negative curvature fibers made with As_2S_3 chalcogenide glass. We change the tube thickness and gap between the cladding tubes to find the optimum structure that can simultaneously provide low transmission loss at wavelengths of 1.5 μm and 4.5 μm. We study negative curvature fibers with both six and eight tubes.

II Simulation and results

1. Negative curvature fiber with six cladding tubes

We first simulate the leakage loss as a function of gap and tube thickness for negative curvature fibers with six cladding tubes. In our simulation, the core diameter is 100 μm. The refractive indices of As_2S_3 glass are 2.44 and 2.41 at wavelengths of 1.5 μm and 4.5 μm, respectively [11]. The material losses of As_2S_3 glass are 2 dB/m and 0.15 dB/m at wavelengths of 1.5 μm and 4.5 μm, respectively [12]. Figure 1(a) shows the loss at wavelength of 1.5 μm. When the tube thickness increases from 0.5 μm to 2.5 μm, there are several high loss regions and low loss regions, which correspond to resonant and antiresonant conditions, respectively [13]. In the low transmission region, when the gap increases from 2 μm to 30 μm, the loss decreases first, and then increases, which means that an appropriate gap should be selected to realize low loss transmission [14]. Figure 2(b) shows the loss at wavelength of 4.5 μm. For a larger wavelength, we see less loss peaks as thickness changes from 0.5 to 2.5 μm, which agrees with the resonant condition, $2t(n^2-1)^{1/2} = m\lambda$, where t is the tube thickness, λ is the resonant wavelength, and m is the order of resonance [13,15].

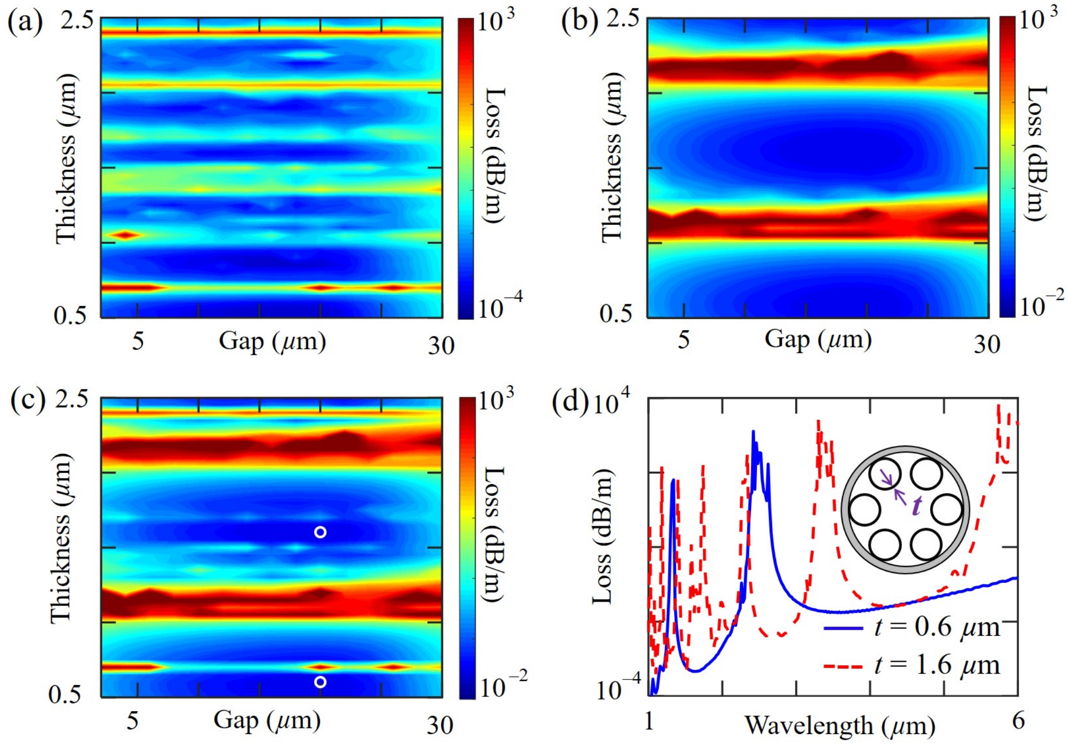

Figure 1. Contour plot of leakage loss at wavelengths of (a) 1.5 μm and (b) 4.5 μm using negative curvature fibers with six cladding tubes. (c) Contour plot of sum of leakage loss at wavelengths of 1.5 μm and 4.5 μm. The white circles indicate the parameters that give low sum losses. (d) Loss as a function of wavelength for a fiber with a tube thickness of 0.6 μm and a fiber with a tube thickness of 1.6 μm, corresponding to the white circles in Fig. 1(c). The gap is 20 μm. Inset shows a schematic of the cross section of the fiber with six cladding tubes.

In order to find a gap and a tube thickness that can realize low loss for both wavelengths of 1.5 μm and 4.5 μm, we sum the losses for wavelengths at 1.5 μm and 4.5 μm and show the new contour plot in Fig. 1(c). In the hollow-core fiber lasers filled with H_2 or N_2O gases, the pump light propagates in the fiber at 1.5 μm before the conversation of light at 4.5 μm. Hence, the sum of the loss at the wavelengths of 1.5 μm and 4.5 μm gives a good indication of the overall loss of the fiber laser. Both the high-loss pattern features of Figs. 1(a) and 1(b) can be observed in Fig. 1(c). There are several low-loss regions when the tube thickness changes. We use two white circles to mark the fiber parameters that give low loss in Fig. 1(c), which can provide low loss transmission for both wavelengths of 1.5 μm and 4.5 μm. We further ran simulations for fiber loss as a function of wavelength using the optimum fiber parameters that are marked with white circles in Fig. 1(c). In Fig. 1(d), we show the result with a gap of 20 μm. The blue solid curve and red dashed curve show the losses for the fibers with tube thicknesses of 0.6 μm and 1.6 μm, respectively. For both fibers, the losses are about of 10^{-3} dB/m and 10^{-2} dB/m at wavelengths of 1.5 μm and 4.5 μm, respectively. At a wavelength of 1.5 μm, a fiber with a thinner tube wall of 0.6 μm, corresponding to lower order of antiresonance, yields a significant wider bandwidth of 0.8 μm than a narrower bandwidth of 0.1 μm for a fiber with a thicker tube wall of 1.6 μm, corresponding to higher order of antiresonance. Here, we evaluate bandwidth as the transmission window with a loss below 10^{-2} dB/m.

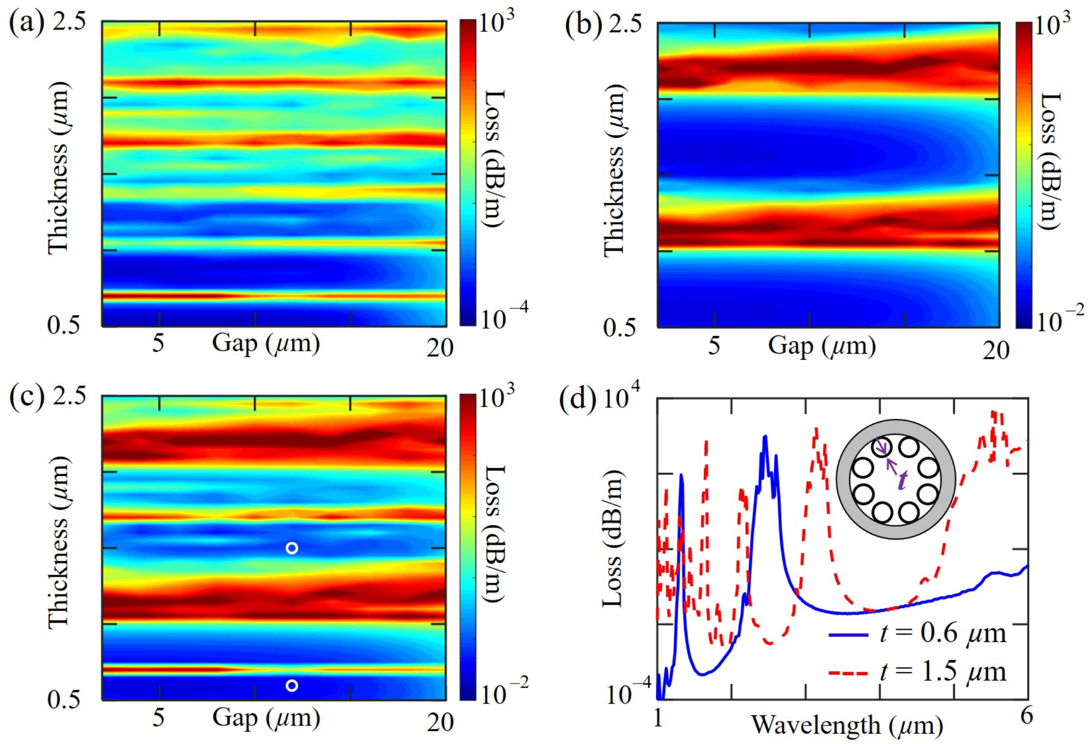

Figure 2. Contour plot of leakage loss at wavelengths of (a) 1.5 μm and (b) 4.5 μm using negative curvature fibers with eight cladding tubes. (c) Contour plot of sum of leakage loss at wavelengths of 1.5 μm and 4.5 μm. The white circle indicates the parameters that gives a low sum loss. (d) Loss as a function of wavelength for a fiber with a tube thickness of 0.6 μm and a fiber with a tube thickness of 1.5 μm, corresponding to the white circles in Fig. 2(c). The gap is 12 μm. Inset shows a schematic of the cross section of the fiber with eight cladding tubes.

2. Negative curvature fiber with eight cladding tubes

We now study the leakage loss for negative curvature fibers with eight cladding tubes. Figures 2(a) and 2(b) show the loss at wavelengths of 1.5 μm and 4.5 μm, respectively. Figure 2(c) shows the sum of leakage loss at wavelengths of 1.5 μm and 4.5 μm as a function of gap and tube thickness. Again, the fiber parameters that yield low loss are marked with white circles in Fig. 2(c). Figure 2(d) shows the loss as a function of wavelength for both two fibers with a gap of 12 μm. The blue solid curve and red dashed curve show the losses for the fibers with tube thicknesses of 0.6 μm and 1.5 μm, respectively. Both fibers yield a loss that is lower than 0.1 dB/m at wavelengths of 1.5 μm and 4.5 μm. When the wavelength is 1.5 μm, the losses in a fiber with a tube thickness of 1.5 μm is 40 times higher than the fiber loss in a fiber with a tube thickness of

0.6 μm. When the tube diameter is small, a thick tube does not serve as an antiresonant layer well and cannot confine the light well at a shorter wavelength [10].

III Conclusion

In conclusion, we study negative curvature fibers with six and eight cladding tubes in order to simultaneously obtain low loss transmission at wavelengths of 1.5 μm and 4.5 μm. Using six cladding tubes, negative curvature fibers with tube thicknesses of 0.6 μm and 1.6 μm yield a similar loss at both 1.5 μm and 4.5 μm. However, the fiber with the thinner tube thickness of 0.6 μm yields a broader bandwidth of 0.4 μm by contrast to the fiber with the thicker tube thickness of 1.6 μm that yields a narrower bandwidth of 0.1 μm. Using eight cladding tubes, a negative curvature fiber with a tube thickness of 0.6 μm yields a 40 times lower loss at wavelength of 1.5 μm than does a fiber with a tube thickness of 1.5 μm. Our study shows that it is possible to realize low loss transmission for wavelengths at 1.5 μm and 4.5 μm using one negative curvature fiber, which is crucial for gas-filled fiber lasers that require low-loss transmission of both pump and lasing wavelengths.

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