

Article

An Enhanced Genetic Algorithm for Optimization of Seven-Tube Single-Ring Anti-Resonant Hollow-Core Fiber with Record-Low Loss and Single Mode

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Abstract

An enhanced genetic algorithm (EGA) is proposed to optimize our previously reported seven-tube single-ring anti-resonant hollow-core fiber (SR-ARF) with a record-low loss of 4.30 dB/km at 1080 nm. Taking advantage of an improved roulette wheel selection and a threshold elimination mechanism, the EGA effectively prevents premature convergence and enhances optimization efficiency. By adopting the proposed EGA to optimize fiber structural parameters, the confinement loss of the seven-tube SR-ARF is further reduced to 2.79 dB/km, and the higher-order mode extinction ratio reaches 204 at 1080 nm, confirming robust single-mode operation. The single-mode operation bandwidth reaches up to 240 nm, covering 920 to 1160 nm. According to the optimized structural parameters, we experimentally fabricated a seven-tube SR-ARF, of which the transmission loss is reduced to 3.29 dB/km at 1052 nm and 3.90 dB/km at 1080 nm, while maintaining near-diffraction-limited single-mode guidance with an M^2 of 1.07/1.05. The proposed EGA model is of great significance for the structural parameter optimization of hollow-core fibers.

Keywords: anti-resonant hollow-core fiber; genetic algorithm; low loss; single mode

1. Introduction

High-power fiber lasers are indispensable tools in advanced manufacturing [1], biomedicine [2], and scientific research [3]. However, conventional solid-core fibers exhibit severe nonlinear effects [4] and laser-induced damage [5] as output power scales up, making it difficult to satisfy the stringent demands of high-power flexible delivery. Hollow-core fibers (HCFs), which confine over 99% of light in the air core [6,7], offer advantages such as low loss, low nonlinearity, and a high damage threshold [8], making them a promising candidate for flexible high-power laser delivery [9].

In the past decade, substantial efforts have been devoted to reducing the transmission loss of HCFs in the 1 μ m wavelength region. Early attempts using a 37-cell photonic bandgap HCF achieved a loss of 12.30 dB/km at 1047 nm [10]. Subsequently, a Kagome HCF was demonstrated with a loss of 8.50 dB/km at 1030 nm [11]. More recently, our group reported a seven-tube single-ring anti-resonant hollow-core fiber (SR-ARF) with a record-low loss of 4.30 dB/km at 1080 nm, representing the lowest loss ever achieved in the 1 μ m band [12]. Despite these advances, further performance improvement of



Received: 3 June 2026

Revised: 7 July 2026

Accepted: 13 July 2026

Published: 15 July 2026

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HCFs remains challenging due to the multi-parameter nature of the fiber structure. Traditional manual optimization is time-consuming and prone to local optima, which has motivated the widespread application of intelligent algorithms for fiber design. Indeed, intelligent algorithms have been widely applied in the optimization of micro-nano optical devices [13–21], including polarization filtering [14], dispersion compensation [20], and confinement loss (CL) reduction in anti-resonant HCFs [15–17]. However, existing algorithms often suffer from premature convergence and limited optimization efficiency when dealing with multi-objective problems involving both low loss and single-mode operation. Furthermore, the systematic optimization of a seven-tube SR-ARF in the 1 μm band using intelligent algorithms remains largely unexplored.

In this paper, we propose an enhanced genetic algorithm (EGA) with a customized fitness function to optimize the structural parameters of a seven-tube SR-ARF in the 1 μm wavelength region. Unlike conventional genetic algorithms, the proposed EGA incorporates an improved roulette wheel selection (IRWS) and a threshold elimination mechanism (TEM) to prevent premature convergence and enhance optimization efficiency. The optimization results demonstrate that the CL of the seven-tube SR-ARF can be further reduced to 2.79 dB/km at 1080 nm, while maintaining robust single-mode operation with a higher-order mode extinction ratio (HOMER) of 204. A broadband single-mode operation bandwidth of 240 nm, covering the wavelength range from 920 to 1160 nm, is also achieved. Furthermore, based on the optimized structural parameters, we experimentally fabricate a seven-tube SR-ARF using the stack-and-draw technique. The measured transmission loss reaches a record minimum of 3.29 dB/km at 1052 nm and a breakthrough low loss of 3.90 dB/km at 1080 nm. Beam quality measurements yield M^2 values of 1.07 and 1.05 in the horizontal and vertical directions, respectively, confirming near-diffraction-limited single-mode guidance. These results validate the effectiveness of the proposed algorithm. Overall, the EGA provides a powerful and efficient tool for the structural parameter optimization of HCFs.

2. Methods and Principle

Figure 1 illustrates the flowchart of the proposed EGA, where both the input and output are the structural parameters of the SR-ARF to be optimized. In our work, these parameters include the core diameter (D_{core}), the cladding tube inner diameter (D), and the wall thickness (T) of the SR-ARF.

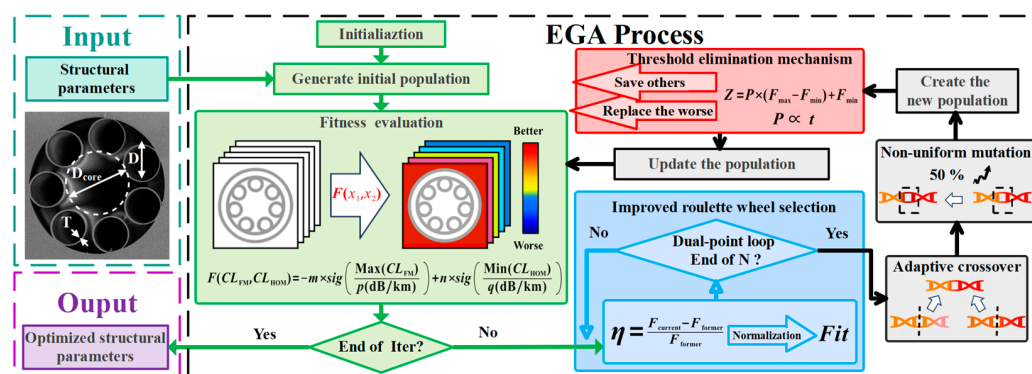


Figure 1. The flowchart of the EGA process.

The selection of a seven-tube configuration is rooted in the inhibited coupling mechanism, which requires a strict balance between mode index mismatch and field overlap [9,22]. Specifically, configurations with fewer tubes (e.g., $N = 6$) create larger gaps that increase fundamental mode (FM) leakage, while those with more tubes (e.g., $N \geq 8$) result in

narrow gaps that trap higher-order modes (HOMs) and degrade single-mode operation. The seven-tube structure provides an optimal physical balance, minimizing FM loss while allowing sufficient HOM leakage, and thus serves as the ideal baseline for our algorithm optimization. The EGA process begins with the random generation of an initial population based on initialization parameters, followed by a fitness evaluation. The fitness evaluation uses a weighted multi-objective fitness function F to comprehensively evaluate the optimization performance in terms of loss and single-mode operation, expressed as:

$$F(\text{CL}_{\text{FM}}, \text{CL}_{\text{HOM}}) = -m \times \text{sig} \left[\frac{\text{Max}(\text{CL}_{\text{FM}})}{p(\text{dB/km})} \right] + n \times \text{sig} \left[\frac{\text{Min}(\text{CL}_{\text{HOM}})}{q(\text{dB/km})} \right] \quad (1)$$

where CL_{FM} and CL_{HOM} represent the CLs of the FM and HOMs, respectively; m and n are weight parameters used to adjust the relative weight of the two indices to control optimization direction; and p and q are optimization interval parameters that map the maximum value of CL_{FM} ($\text{Max}(\text{CL}_{\text{FM}})$) and minimum value of CL_{HOM} ($\text{Min}(\text{CL}_{\text{HOM}})$) to the range from 0 to 1.

After the fitness evaluation, if the maximum iteration number (Iter) is reached, the optimized individuals (i.e., the optimized fiber structural parameters) are output, and the optimization process ends. Otherwise, the iteration continues. During the iterative process, an IRWS and TEM are introduced. As shown in the blue region of Figure 1, the IRWS enhances population diversity and evolutionary potential by using an optimization ratio (η) instead of the fitness value as the basis for selection probabilities, thereby dynamically adjusting selection pressure and mitigating premature convergence. The optimization ratio η is defined as:

$$\eta = \frac{F_{\text{current}} - F_{\text{former}}}{F_{\text{former}}} \quad (2)$$

where F_{current} is the fitness value of the current individual, and F_{former} is the fitness value of the optimal individual from the previous iteration. Subsequently, η is normalized to generate the final selection probability. This process helps ensure that all individuals maintain a positive probability, preserving potentially valuable genetic combinations for subsequent evolution. It is efficiently implemented through batch iteration and sorting of random numbers, combined with a dual-pointer loop. This approach ensures that each random number and cumulative probability value is compared only once, and the process repeats until N individuals are selected.

The TEM, as shown in the red region in Figure 1, aims to reduce ineffective iterations and accelerate convergence. A dynamic threshold Z is used, where individuals with fitness below Z are replaced by the current optimal individual, while the remaining individuals are retained. The threshold Z is defined as:

$$Z = P \times (F_{\text{max}} - F_{\text{min}}) + F_{\text{min}} \quad (3)$$

where F_{min} and F_{max} represent the minimum and maximum fitness values of the current population, respectively, and P is the individual elimination rate, which is positively correlated with the current iteration count to a certain degree. It is dynamically adjusted at different stages and is defined as:

$$P = \begin{cases} P_{\text{min}}, t \leq t_{o1} \\ P_{\text{min}} + (P_{\text{max}} - P_{\text{min}}) \times \frac{t - t_{o1}}{t_{o2} - t_{o1}}, t_{o1} \leq t \leq t_{o2} \\ P_{\text{max}}, t \geq t_{o2} \end{cases} \quad (4)$$

where $P_{\min}$ and $P_{\max}$ represent the minimum and maximum elimination rates, respectively; t_{o1} and t_{o2} are the time points for linear growth of the elimination rate, and t is the current iteration number.

Between the IRWS and TEM, the algorithm performs adaptive crossover [23] and non-uniform mutation [24]. Two parent individuals exchange genes at random crossover points to generate offspring; if duplicate offspring are produced, crossover is repeated. Then, non-uniform mutation is applied to a randomly selected one-third of the offspring genes, with a 50% probability of increase or decrease. This process is repeated to generate a new population.

3. Experimental Results

The three structural parameters of the seven-tube SR-ARF used as the input of the EGA are listed in Table 1. Within the predefined parameter range, we randomly generate twenty sets of structural parameters (individuals) as the initial population for the EGA. The CL for each individual at 1064 nm is calculated using COMSOL Multiphysics 6.1 software. Subsequently, the simulated CLs are input into the fitness function for individual update and iteration. The optimization conditions are defined as follows: the CL_{FM} is below 5 dB/km, and the CL_{HOM} exceeds 500 dB/km, ensuring effective single-mode operation with a HOMER greater than 100. Based on our iterative optimization results and the need to maintain a balanced convergence between the low-loss and single-mode objectives during the comparison, the fitness function coefficients are set as $p = 0.35$, $q = 50$, $m = 0.80$, and $n = 0.20$. The optimization process is conducted on a 16-core CPU with 128 GB of memory, requiring approximately 24 h.

Table 1. Structural parameters of the seven-tube SR-ARF.

Parameters	Description	Min	Max	Step-Size
D_{core}	Core radius (μm)	30	55	1 μm
D/D_{core}	The ratio of D to D_{core}	0.50	0.75	0.001
T	Thickness of cladding tube (nm)	710	820	1 nm

The optimized SR-ARF is designed to operate in the second anti-resonant transmission band. Although the first band theoretically offers the lowest confinement loss [22,25], it requires extremely thin silica walls ($<0.35 \mu\text{m}$ at a $\sim 1 \mu\text{m}$ wavelength) that pose severe fabrication challenges [26]. Targeting the second band doubles the required wall thickness. This thicker geometry provides stronger resistance against hole-collapsing during the fiber drawing process [12], ensuring the structural symmetry and high fabrication yield necessary to validate our “algorithm-to-fabrication” closed-loop framework.

Figure 2 shows the evolution of CL at 1064 nm and fitness values during the optimization process. The CL_{FM} stabilizes at 2.60 dB/km after the 10th iteration, while CL_{HOM} fluctuates within the first 12 iterations, then increases and stabilizes at 530 dB/km after the 25th iteration. By contrast, the fitness values converge rapidly by the 10th iteration, with the average fitness value remaining consistently around 0.19. The evolution of these values indicates that low-loss and single-mode performance can be optimized within 30 iterations, demonstrating that the proposed algorithm possesses fast convergence characteristics [17,18,20,21].

With the maximum iteration number set to 30, the final optimization results are illustrated in Figure 3. As shown in Figure 3, there are 21 optimized individuals (red points). All optimized individuals achieve single-mode operation with a HOMER higher than 150 and CL_{FM} lower than 4.30 dB/km, indicating that they satisfy the optimization conditions.

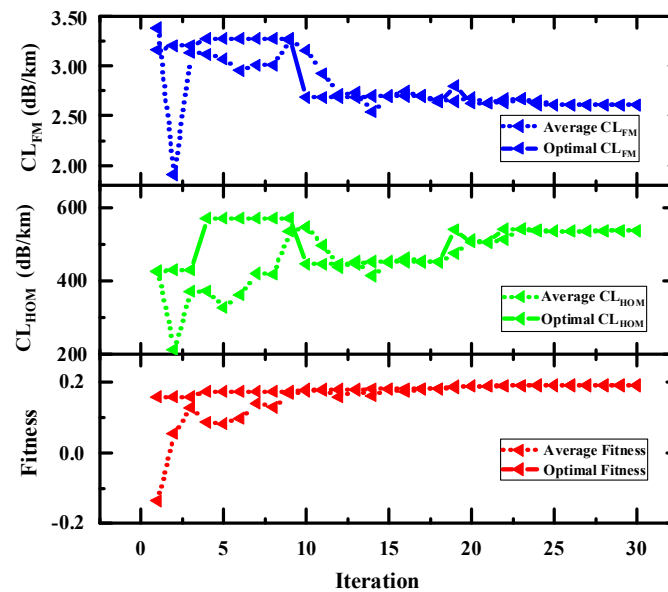


Figure 2. The evolution of CL and fitness values during the optimized process.

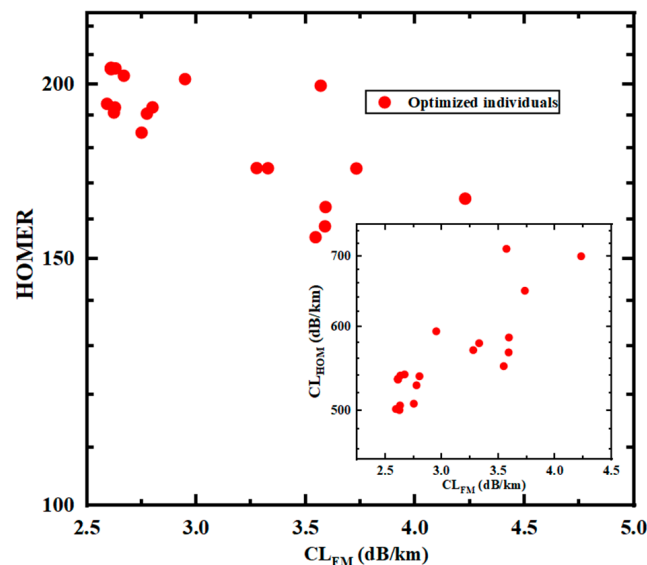


Figure 3. CL and HOMER of the optimized individuals.

Figure 4 shows the structural parameters and fitness values of the 21 optimized individuals. The color bar represents fitness values, with the optimized individuals (red points) exhibiting the highest fitness values among all individuals (blue points), demonstrating superior performance that meets the optimization conditions. The D_{core} values of these optimized individuals are concentrated in the 41–43 μm range, consistent with the theoretical expectation that larger core diameters can reduce CL_{FM} [27–29]. However, further diameter expansion is limited by the optimization conditions, which require maintaining sufficient CL_{HOM} despite the simultaneous reduction in CL_{FM} . The D/D_{core} values are primarily distributed in the range of 0.71–0.73. The T values are mainly distributed over a relatively wide range of 740–810 nm, suggesting their weaker influence on performance. The structural parameters of the optimized individuals are consistent with those of the fabricated fiber [11] in terms of core diameter and wall thickness. Further optimization should focus on increasing the D/D_{core} ratio to enhance loss and single-mode characteristics.

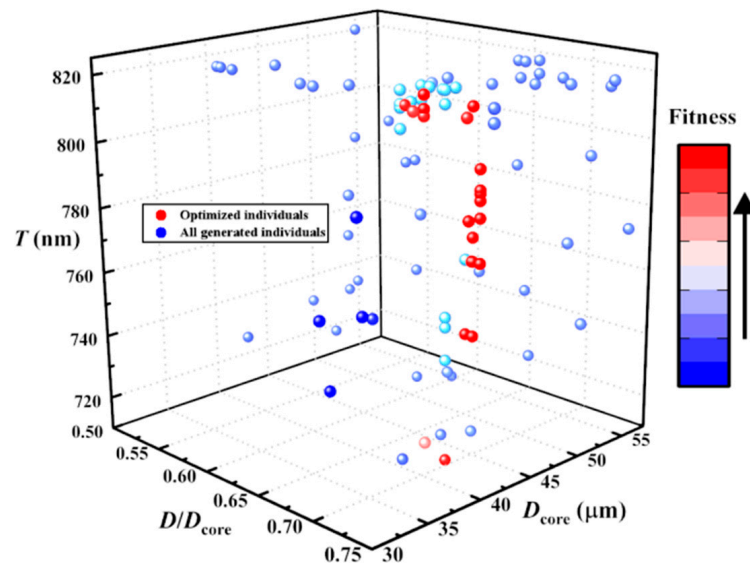


Figure 4. Structural parameters and fitness values of the optimized individuals.

Since the algorithm optimization is conducted at a single operating wavelength, we also simulated the transmission characteristics of the optimized individuals around the 1 μm band. Figure 5 shows the CL curves of four representative individuals: the one with the minimum CL_{FM} , the one with the maximum HOMER, the one with the CL_{FM} closest to the average value of the 21 optimized individuals, and the one with the HOMER closest to the average value. The detailed structural parameters and performance are provided in Table 2. The solid and dotted lines represent CL_{FM} and CL_{HOM} , respectively. All four individuals exhibit a flat low-loss single-mode transmission band near 1 μm , with CL_{FM} lower than 5 dB/km and HOMER higher than 100. The maximum low-loss single-mode operation bandwidth reaches 240 nm, covering the wavelength range from 920 to 1160 nm, as indicated by individual 2 (green background). These results indicate that the seven-tube SR-ARF holds potential for further optimization, with CL_{FM} reducible to 2.79 dB/km and CL_{HOM} increasing to 569 dB/km at 1080 nm while maintaining robust single-mode operation with a HOMER of 204.

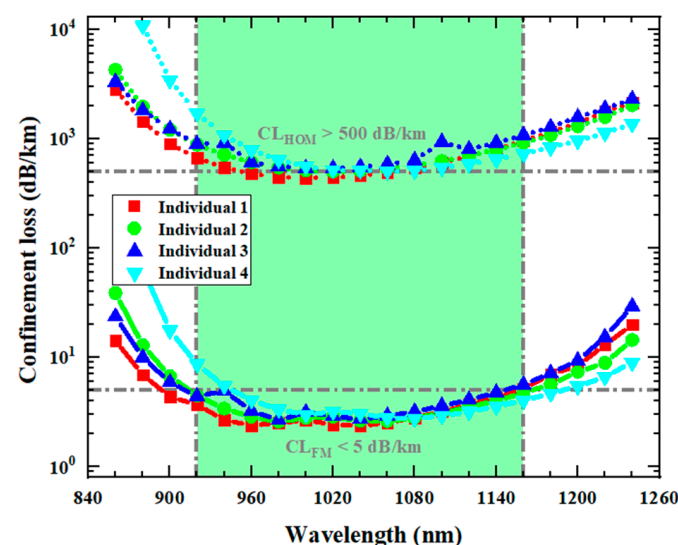


Figure 5. Transmission characteristics of four representative individuals.

Table 2. Structural parameters and performance of four representative individuals at 1064 nm.

Individual	D_{core} (μm)	T (nm)	D/D_{core}	Max (CL_{FM}) (dB/km)	Min (CL_{HOM}) (dB/km)	HOMER
Individual 1	43	780	0.717	2.59	502	194
Individual 2	43	794	0.723	2.61	536	206
Individual 3	42	786	0.722	2.95	595	202
Individual 4	43	817	0.711	2.77	529	191

To evaluate the impact of the IRWS and the TEM, a comparative experiment is conducted with the same initial population and iteration number. The fitness function parameters are set as $p = 0.50$, $q = 50$, $m = 0.50$, and $n = 0.50$. Figure 6 shows the evolution of fitness values during the optimization process, where the solid and dotted lines represent the optimal fitness and the average fitness, respectively. The average fitness of the conventional genetic algorithm (GA) exhibits slow growth and significant fluctuations within the first 25 iterations, resulting in a substantial gap from the optimal fitness at the 30th iteration. This phenomenon is primarily attributed to the reduced efficiency of standard roulette wheel selection when dealing with the mixed positive and negative fitness values in the early iterations and diminished fitness differentials in later iterations. In contrast, the introduction of IRWS leads to a continuous rise in the average fitness after five iterations, gradually approaching the optimal fitness with smaller differences after the 27th iteration, which improves selection efficiency and convergence; however, full convergence is not achieved within 30 iterations. Building upon this, the addition of TEM facilitates a significant acceleration in the rise in the average fitness through the threshold-based elimination of inferior individuals, achieving convergence while obtaining the highest optimal fitness at the 21st iteration. This indicates that TEM reduces redundant iterations, promotes stable population convergence, and enhances global search capability simultaneously. The synergistic effect of both methods enables the GA to converge with a smaller population within a limited number of iterations, obtaining better optimization results compared to the conventional GA.

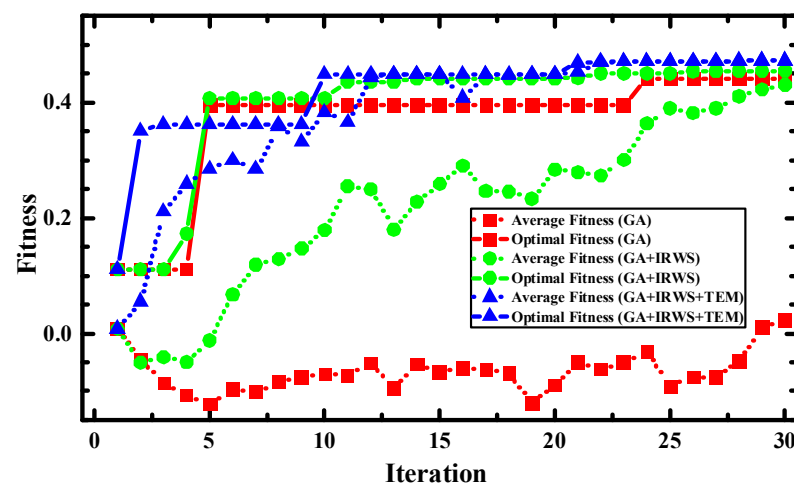


Figure 6. The evolution of fitness values during the optimization process.

To highlight the superiority of the EGA optimization, we compare the optimization results obtained using different algorithms. From the optimized individuals generated by each algorithm, two representative individuals (the ones with CL_{FM} and HOMER closest to the average values of the optimized individuals, respectively) are selected for transmission characteristic evaluation. Figure 7 shows the CL curves of these selected individuals around the 1 μm band, with red, green, and blue lines representing the results optimized by EGA,

GA, and simulated annealing (SA), respectively. Compared to the individuals optimized by GA, those optimized by EGA and SA both achieve a wider single-mode operation bandwidth near 1 μm , with a CL_{FM} lower than 5 dB/km and a HOMER higher than 100. However, across the transmission band, the individuals optimized by EGA exhibit a lower CL_{FM} level compared to those optimized by SA. Overall, for the optimization of structural parameters for the seven-tube SR-ARF, the EGA exhibits superior performance. In summary, the practical advantage of the proposed EGA over conventional optimization methods lies in its robust stability and superior capability to consistently locate the high-quality global optimum, avoiding being trapped in local optima even when confronted with highly nonlinear, multi-parameter structural variations.

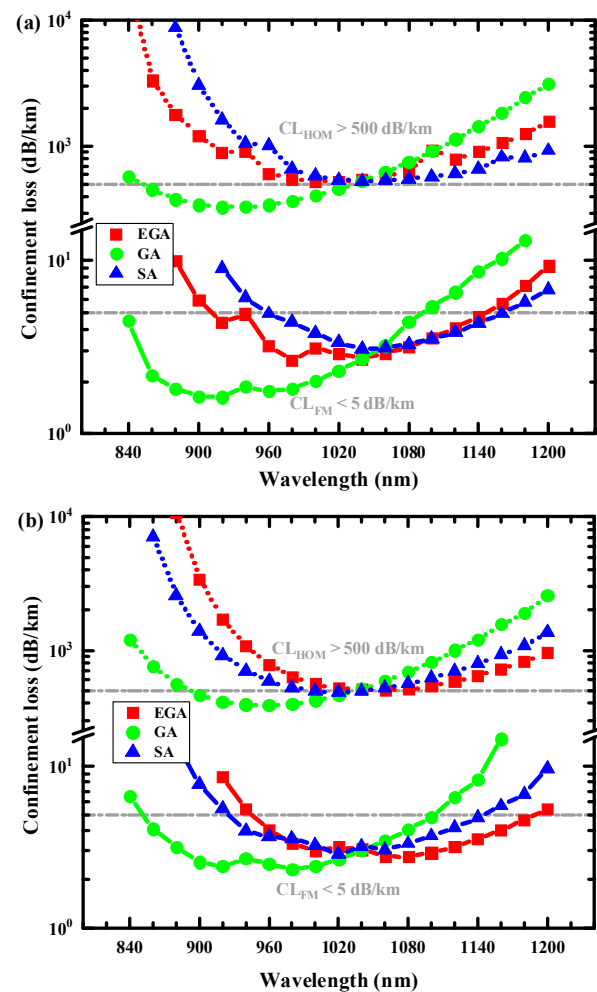


Figure 7. Transmission characteristics of representative individuals optimized by different algorithms. (a) Individuals with the CL_{FM} closest to the average value of the optimized individuals; (b) individuals with the HOMER closest to the average value of the optimized individuals.

Based on the optimized parameters, we fabricated a seven-tube SR-ARF using the stack-and-draw technique with Heraeus F300 fused silica. The fabricated fiber (Figure 8a, inset) features a 43 μm core diameter and a 31 μm average cladding tube diameter, yielding $D/D_{\text{core}} = 0.72$. Transmission loss was measured via the cut-back method with the fiber loosely coiled on a 1 m-diameter spool to minimize bend-induced attenuation. The measured spectrum (Figure 8a, red line) reveals a minimum loss of 3.29 dB/km at 1052 nm, closely approaching the simulated CL of 2.79 dB/km (blue line). This slight discrepancy ($\sim 0.5 \text{ dB/km}$) arises because the experimental total loss encompasses additional mechanisms, primarily surface scattering loss (SSL) and minor material absorption. Operating

near 1 μm , the fiber lies in a transitional spectral regime where SSL (scaling as λ^{-3}) acts as a non-negligible contributor, comprehensively accounting for the measured loss difference [8].

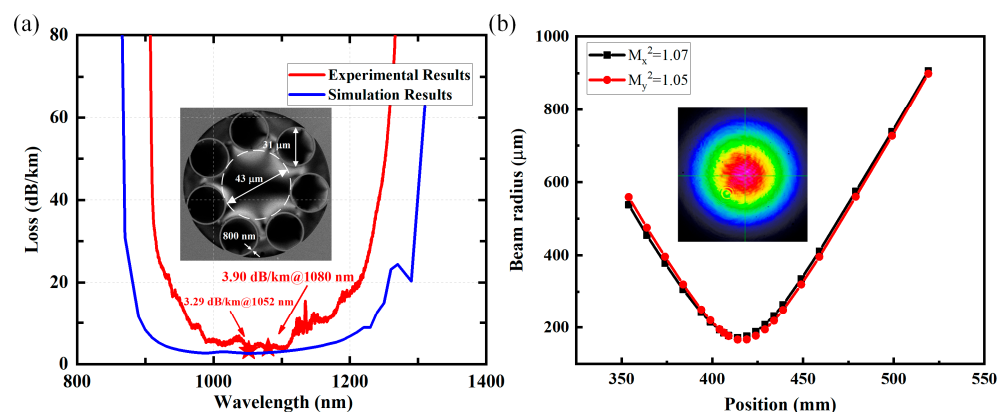


Figure 8. (a) Transmission loss spectra of the fabricated seven-tube SR-ARF. Inset: SEM images of the fabricated fiber; (b) M^2 measurement results. Inset: Near-field intensity profile of the output beam.

Regarding the transmission bandwidth, the experimental low-loss window (total loss < 5 dB/km) spans 70 nm (1042 nm to 1112 nm), compared to the 240 nm simulated bandwidth (CL < 5 dB/km and HOMER > 100). This reduction occurs primarily because the measured SSL and inevitable bending effects elevate the baseline of the entire loss spectrum. Furthermore, the steeper loss increases at the band edges relative to the ideal simulation is attributed to longitudinal non-uniformities in the cladding wall thickness (averaging ~ 800 nm) and physical bending during measurement. Such longitudinal structural fluctuations cause localized shifts in the resonance conditions along the fiber, effectively narrowing the transmission window. Detailed quantitative analysis and figures regarding the fabrication tolerance of the structural parameters (D_{core} , D/D_{core} , and T) on the confinement loss and HOMER are provided in the Supplementary Material. Nevertheless, when evaluated under a standard < 20 dB/km threshold [12], the fabricated fiber still demonstrates a broad 280 nm transmission bandwidth (935 nm to 1215 nm).

The beam quality of the fabricated fiber was characterized by the beam propagation factor (M^2 , Beam-Squared BSQ-SP920, Ophir, Jerusalem, Israel). As shown in Figure 8b, M^2 measurements yielded values of 1.07 and 1.05 in the horizontal and vertical directions, respectively, confirming near-diffraction-limited single-mode operation across the operational band. The inset of Figure 8b displays the corresponding near-field intensity profile, which exhibits an excellent near-Gaussian distribution, further confirming robust single-mode operation. The achieved combination of record-low loss and excellent modal purity proves the superiority of our optimization algorithm.

4. Conclusions

In this paper, we have proposed an EGA featuring a customized fitness function to optimize the structural parameters of seven-tube SR-ARFs. Driven by the synergistic effect of IRWS and TEM, the EGA demonstrates superior optimization efficiency and effectiveness compared to conventional GA and SA, rapidly avoiding local optima and converging within 30 iterations. While requiring a similar raw computational time frame as conventional algorithms (which is primarily dominated by the finite element simulations), the EGA provides a crucial practical advantage by strictly guaranteeing the discovery of a high-quality global optimum within the same computational cost. The theoretically optimized fiber exhibits a CL of 2.79 dB/km and a high HOMER of 204 at 1080 nm, robustly guaranteeing single-mode operation. Furthermore, it delivers a broad single-

mode bandwidth of 240 nm, spanning from 920 to 1160 nm. To validate the algorithm's practical viability, we successfully fabricated the optimized fiber design. The fabricated fiber achieves a record minimum transmission loss of 3.29 dB/km at 1052 nm and 3.90 dB/km at 1080 nm, alongside near-diffraction-limited single-mode guidance ($M^2 = 1.07/1.05$). These experimental milestones strictly corroborate the precision and practical value of the proposed EGA. While this study focuses on exploring the fundamental limits of SR-ARFs at 1 μm , the proposed EGA framework is inherently universal. Future work will extend this method to optimize more complex structures, such as nested anti-resonant fibers, and target specific advanced properties including bending resistance, polarization maintenance, and applications in the less-explored VUV and MIR wavelength regions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/photonics13070674/s1>, Figure S1: Influence of D_{core} fabrication error on CL and HOMER. (a) CL_{FM} and CL_{HOM} ; (b) HOMER.; Figure S2: Influence of D/D_{core} fabrication error on CL and HOMER. (a) CL_{FM} and CL_{HOM} ; (b) HOMER.; Figure S3: Influence of T fabrication error on CL and HOMER. (a) CL_{FM} and CL_{HOM} ; (b) HOMER.

Author Contributions: Methodology, W.G. and A.L.; Software, W.G. and A.L.; Validation, W.G., Y.G. and X.W.; Formal analysis, W.G. and Y.G.; Resources, W.G. and Y.G.; Writing – original draft, W.G. and A.L.; Writing – review & editing, S.L., X.W. and Z.L.; Visualization, W.G.; Supervision, S.L., X.W. and Z.L.; Project administration, Z.L.; Funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Fundamental Research Funds for the Central Universities 2025YJS013, and the National Natural Science Foundation of China (No. 12174022).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: Author Zhenggang Lian is the employee of Yangtze Optical Electronic Co. Ltd., Wuhan 430205, China. All the authors declare no conflicts of interest.

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