Design of Air-Trenches/Holes Assisted Depressed-Core 12-Mode Fiber for Less MIMO Space Division Multiplexing

Miaofang Zhou, Ping Jiang, Huajun Yang, Weinan Caiyang, Yan Qin, and Yifan Zheng

School of Physics, University of Electronic Science and Technology of China, Chengdu 610054, China
Corresponding author: Huajun Yang (e-mail: yanghj@uestc.edu.cn). This work was supported by the National Natural Science Foundation of China (NSFC) under Grant 11574042 and Grant 61271167.

ABSTRACT An air-trenches/holes assisted depressed-core few-mode fiber (AT-AH-DC-FMF) that features some asymmetrical air trenches, airholes and a depressed step-index core is proposed in this paper. The AT and DC can produce great contribution in separating the non-degenerated LP modes and spatial modes, thus suppressing the crosstalk efficiently. Based on AT and AH, the bending loss values of AT-AH-DC-FMF can be satisfied with the ITU-T recommendations of G.654. The simulation results indicate that our proposed fiber can support 12 spatial modes with the effective index difference between adjacent LP modes (Δn_{eff}) larger than 1.03×10^{-3} and the effective index difference between adjacent spatial modes (δn_{eff}) larger than 1.24×10^{-4}. The broadband characteristics such as Δn_{eff}, δn_{eff}, chromatic dispersion and effective mode field area (A_{eff}) over the whole C and L band are comprehensively investigated. Moreover, fabrication methods and birefringence are detailed discussed. Our proposed AT-AH-DC-FMF possesses great potential to be applied to less multiple-input multiple-output (MIMO-less) space-division multiplexing (SDM) enlarging optical communication capacity and simplifying the system complexity.

INDEX TERMS Few mode fibers, optical fiber communications, space division multiplexing, broadband characteristics, Holes-assisted.

I. INTRODUCTION With the widespread of big data and cloud computing, the amount of data tends to an explosive growth [1]. The current data centers and optical networks are rapidly reaching their ultimate capacity due to the nonlinear Shannon limit of single-mode fibers (SMFs) [2]-[4]. Space division multiplexing (SDM) systems based on multi-core fiber (MCF) and few-mode fiber (FMF) have been extensively investigated for their potential to overcome these looming communication bottlenecks [5]-[7]. However, the high-performance MCF with some characteristics such as high core density, low crosstalk and low loss simultaneously faces a large number of technical challenges in the design and manufacturing process. It is also challenging to efficient couple signals in and out after all cores are tightly packed in a MCF with a limited cladding size [8]. FMF with its relatively simple structure produces unique advantages in terms of manufacturing methods and connectivity with standard SMFs. In addition, FMF with broadband characteristics over a wide wavelength range can provide the opportunities for SDM compatible with the mature wavelength-division multiplexing (WDM) technique [9]. The most crucial issue encountered in FMF is the crosstalk among different modes [10]. Employing the multiple input multiple output (MIMO) processing at the receivers is one of the approaches to settle this issue [11]-[13]. But the complexity of MIMO increases nonlinearly with the number of propagation modes, thus resulting in the depleting of the digital signal processing (DSP) capacity and the consumption of electric power [14]. To simplify MIMO, it is necessary to design special weakly-coupled FMF whose effective index difference between non-degenerated propagate modes (Δn_{eff}) is larger than 10^{-3}. Moreover, MIMO can be eliminated by enlarging the effective index difference between adjacent degeneracy modes (δn_{eff}) to larger than 10^{-4}. This method would be well satisfied with short-reach transmission such as data centers and computer rooms as its advantages of simplify systems...
Recently, researchers have made a large number of attempts in terms of adjusting the effective index \(n_{\text{eff}}\) of higher-order mode to enlarge the effective index difference between adjacent non-degenerated and degeneracy modes [18]-[21]. For example, in [20], a hole-assisted graded-index 4 LP-modes fiber with Min \(\Delta n_{\text{eff}}\) as high as 1.94×10^{-3} is proposed. In [21], a 3 LP-mode ring core fiber with Min \(\Delta n_{\text{eff}}\) as high as 2.5×10^{-3} is designed. However, 4×4 MIMO facilities are still needed to recover their fourfold degeneracy modes. It has been reported in [2], [15], [22], [23] that elliptical core fibers can act as a polarization maintaining fiber (PMF) used for MIMO-free SDM systems. For example, in [15], a 10 polarization-maintaining PANDA ring-core fiber with min \(\Delta n_{\text{eff}}\) of 1.29×10^{-4} has been proposed. In [2], 10 distinctive polarization modes with Min \(\delta n_{\text{eff}}\) of larger than 1.32×10^{-4} have been achieved in a FMF composed of a central circular-hole and an elliptical-ring core. However, drawback of high doping difficulty is induced in those PMF, due to its large core and cladding relative refractive index difference of up to 3%. In addition, the core region of most of the PMF stays at a small value, resulting in a smaller effective mode field area than other FMF. What’s more, PMF with the minimum effective refractive index difference of larger than 1.32×10^{-4} can only be applied in a shorter distance transmission than that of other FMF. Therefore, designing a weakly-coupled FMF with low doping, enough modes, large effective mode field area, sufficient \(\Delta n_{\text{eff}}\), sufficient \(\delta n_{\text{eff}}\) and stable comprehensive broadband characteristics for less MIMO SDM-WDM systems is urgent.

In this paper, we proposed an air-trenches/holes assisted depressed-core 12-mode fiber for 2×2 MIMO SDM systems. COMSOL Multiphysics and MATLAB are utilized for investigating the fiber performance. The main contents of this paper are as follows: (I) In section 2, the schematic topology and particularities of our proposed air-trenches/holes assisted depressed-core few-mode fiber (AT-AH-DC-FMF) are introduced. (II) In section 3, the \(\delta n_{\text{eff}}, \Delta n_{\text{eff}}\) dependence on the parameters of DC and AT are investigated to explain the roles of DC and AT for AT-AH-DC-FMF. Then the bending loss as a function of the parameters of AT and AH is calculated to help the bending loss values of AT-AH-DC-FMF to satisfy the ITU-T recommendations of G. 654. (III) In section 4, the geometrical birefringence and stress birefringence are analyzed. (IV) In section 5, to confirm the compatibility of our proposed AT-AH-DC-FMF with mature WDM technology, the broadband characteristics such as \(\delta n_{\text{eff}}, \Delta n_{\text{eff}}\), \(A_{\text{eff}}\) and chromatic dispersion are comprehensively researched over the whole C and L band. (V) In section 6, the fabrication methods and feasibility of our proposed AT-AH-DC-FMF are briefly discussed.

II. SCHEMATIC TOPOLOGY AND THEORY

Fig. 1 is the schematic of our proposed AT-AH-DC-FMF which composes of a step-index core in the center with some surrounded asymmetric air holes and air trenches, and a circular pure \(\text{SiO}_2\) cladding. A list of parameters are used to describe the geometric structure of AT-AH-DC-FMF, where \(r, d, \theta, \beta, w, p\) are the core radius, the DC radius, the angles of air trenches along \(y\)-axis and \(x\)-axis, the width of air trenches and the radius of air holes, respectively. \(l\) is the distance between air holes and core. Three particularities of our design should be noted: (1) asymmetric air trenches lie closely to the core, which affects the symmetry of the mode fields and the effective index of guided modes directly, producing great contribution in separating the degenerated spatial modes and non-degenerated LP modes; (2) the AT and AH has the maximum refractive index difference to the core, thus it exhibits better capability in reducing the bending loss of higher-order LP modes; (3) compared with bow-tie and steering wheel-type ring structure FMF, our design without complex doping of multi-clad structures and the extreme short gap between special structure and core, thus avoiding the increase of manufacturing complexity.

![FIGURE 1. The schematic diagram and refractive index distribution of AT-AH-DC-FMF.](image)

The refractive index profile of AT-AH-DC-FMF is shown in Fig. 1(c), where \(n_{\text{co}}, n_{\text{de}}, n_{\text{cl}}\) and \(n_{\text{air}}\) represent the refractive index of core, DC, cladding and air holes/trenches. The refractive index profiles in \(x\)-axis and \(k\)-direction are different as the exist of air trenches and air holes. We denote the refractive index difference \(\Delta n_1 = n_{\text{de}} - n_{\text{co}}\) Correspondingly, \(\Delta n_2 = n_{\text{cl}} - n_{\text{co}}\). In this paper, the core parameters with \(r = 8.8\ \mu\text{m}\), \(\Delta n_1 = -0.2\%\) and \(\Delta n_2 = -1.1\%\) support 7-LP-mode (LP_{01}, LP_{11}, LP_{21}, LP_{02}, LP_{31}, LP_{12} and LP_{11}) are employed. Then the detailed numerical simulations are carried out with a finite element mode solver (COMSOL Multiphysics) in the following sections. It has been pointed out in [24] and [25] that a detailed explanation of the analysis method is very important to prove the correctness of a study. Therefore, we list the main
simulation steps as follows: Firstly, establishing the model of our proposed AT-AH-DC-FMF with the “Wave optics” module of COMSOL Multiphysics. Secondly, setting up different materials for different regions of our proposed AT-AH-DC-FMF. Thirdly, setting up a perfectly matched layer (PML) at outmost region of the model to absorb the light escaping out the concerned region. Fourthly, dividing the grid with normal size. Finally, the simulation results can be achieved after the mode analysis.

III. FIBER PARAMETERS SELECTION

A. DC PARAMETERS

To highlight the importance of DC for our proposed AT-AH-DC-FMF, the min $\Delta n_{\text{eff}}$ of the AT-AH-FMF is calculated and presented in Fig. 2 ($\Delta n_1 = 0$). As can be seen from this region, without DC, the min $\Delta n_{\text{eff}}$ with its value of $0.86 \times 10^{-3}$ appears between LP$_{21}$ and LP$_{02}$, indicating that there is a higher possibility of coupling between LP$_{21}$ and LP$_{02}$ during the transmission. This phenomenon is consistent with the results in [5], indicating the correctness of our simulation method. Previous studies have shown that the $n_{\text{eff}}$ of LP modes can be adjusted by changing the refractive index of the core region [5]. Therefore, a DC is added to the center of core to manipulate the $n_{\text{eff}}$ between LP modes, to keep the min $\Delta n_{\text{eff}}$ larger than the threshold value of $1 \times 10^{-3}$. The colormap of min $\Delta n_{\text{eff}}$ between adjacent LP modes dependence on $d$ and $\Delta n_1$ is presented in the other regions of Fig. 2.

![FIGURE 2. The min $\Delta n_{\text{eff}}$ between adjacent LP modes as a function of $d$ and $\Delta n_1$ at the wavelength of 1550 nm.](image)

Fig. 2 shows the min $\Delta n_{\text{eff}}$ between adjacent LP modes as a function of $d$ and $\Delta n_1$ at the wavelength of 1550 nm. In Fig. 2, two black dotted lines indicate that with the variation of $d$ and $\Delta n_1$, the min $\Delta n_{\text{eff}}$ of our proposed AT-AH-DC-FMF appears between different adjacent LP modes. We circle the region that produces great contribution in separating the non-degenerated LP modes with red dotted line. In this region, the min $\Delta n_{\text{eff}}$ between adjacent LP modes can be increased from initial $0.86 \times 10^{-3}$ to $1.06 \times 10^{-3}$.

In addition, the region with $\Delta n_1$ ranging from -1.0% to -0.1% and $d$ ranging from 0.6 to 1.6 $\mu$m shows enough fabrication tolerances. Therefore, to apply our proposed AT-AH-DC-FMF to MIMO-less SDM systems, the parameters of DC ($d$ and $\Delta n_1$) should be selected strictly according to our simulation results. Here, we determine parameters of the DC as $d = 1$ $\mu$m and $\Delta n_1 = -0.2\%$. At this time, the min $\Delta n_{\text{eff}}$ is $1.02 \times 10^{-3}$.

B. AT/AH PARAMETERS

In this section, we aim to find out the optimum parameters of the air trenches, air holes and cladding, so as to achieve the 12-mode AT-AH-DC-FMF. Before setting out to do this work, the first thing we should notice is that the number of LP modes may be decreased after proper air trenches are added to our fiber. The main reason is that the air trenches affect the $n_{\text{eff}}$ of LP mode, resulting in some $n_{\text{eff}}$ of higher-order LP modes (LP$_{12}$ and LP$_{41}$) being less than $n_{\text{cl}}$, which leads to the leakage of some higher-order LP modes. Traditionally, to increase the number of propagation modes, either the radius of core or the refractive index difference between the core and the cladding $|\Delta n_2|$ should be increased. However, the bending loss of the higher-order LP modes may still stay at a high value through this way, and the doping concentration will be increased. Considering the particular structure of our design, four air holes are added to the cladding to reduce the equivalent index of the cladding, so that the effective refractive index of LP$_{12}$ and LP$_{41}$ are larger than the equivalent index of the cladding. So the LP$_{12}$ and LP$_{41}$ can be bound in the core. Then the following steps are taken to select the optimum parameters of the air trenches, air holes and cladding: (1) in Fig. 3, investigating the impact of $\theta$ and $\beta$ on $\Delta n_{\text{eff}}$ and $\delta n_{\text{eff}}$ of our proposed AT-AH-DC-FMF; (2) in Fig. 4(a-c), analyzing the influence of $l$, $w$ and $\Delta n_2$ on the number of modes, min $\Delta n_{\text{eff}}$ and min $\delta n_{\text{eff}}$; (3) in Fig. 4(d), exploring the relationship between the bending loss of AT-AH-DC-FMF, the width of air trenches and the radius of air holes.

![FIGURE 3. The impact of $\theta$ and $\beta$ on $\Delta n_{\text{eff}}$ and $\delta n_{\text{eff}}$ of our proposed AT-AH-DC-FMF.](image)

![FIGURE 4. The influence of $l$, $w$ and $\Delta n_2$ on the number of modes, min $\Delta n_{\text{eff}}$ and min $\delta n_{\text{eff}}$.](image)
To simultaneously keep $\Delta n_{\text{eff}}$ larger than $1 \times 10^{-3}$ and $\delta n_{\text{eff}}$ larger than $1 \times 10^{-4}$, the $\theta$ and $\beta$ should be selected strictly. We present the min $\Delta n_{\text{eff}}$ between adjacent LP modes and the min $\delta n_{\text{eff}}$ between adjacent spatial modes as a function of $\theta$ and $\beta$ at the wavelength of 1550 nm in Fig. 3. In our simulation, we increase the angle $\beta$ from 28 deg to 41 deg with a step size of 1 deg and the angles $\theta$ from 81 deg to 105 deg with a step size of 1 deg. From Fig. 3, it is obvious that the min $\Delta n_{\text{eff}}$ increases with the increase of $\theta$ and $\beta$. In the region of $38 \text{ deg} \leq \beta \leq 41 \text{ deg}$ and $96 \text{ deg} \leq \theta \leq 105 \text{ deg}$, $\Delta n_{\text{eff}}$ is larger than $1 \times 10^{-3}$, however, $\delta n_{\text{eff}}$ is smaller than $1 \times 10^{-4}$. In the region of $28 \text{ deg} \leq \beta \leq 33 \text{ deg}$ and $82 \text{ deg} \leq \theta \leq 95 \text{ deg}$, $\delta n_{\text{eff}}$ is larger than $1 \times 10^{-4}$, however, $\Delta n_{\text{eff}}$ is smaller than $1 \times 10^{-3}$. Both regions should be excluded because they are inconsistent with the above requirements for $\Delta n_{\text{eff}}$ and $\delta n_{\text{eff}}$. We circle the selected region that well satisfies the requirements for $\Delta n_{\text{eff}}$ and $\delta n_{\text{eff}}$ with a black dotted box. The selected region with $\theta$ ranging from 86 deg to 102 deg and $\beta$ ranging from 31 deg to 40 deg indicates that our proposed AT-AH-DC-FMF possesses feasible fabrication tolerance during manufacturing air trenches. Finally, the parameters of air trench are fixed as $\theta = 88 \text{ deg}$ and $\beta = 36 \text{ deg}$. At this time, the min $\Delta n_{\text{eff}} = 1.03 \times 10^{-3}$ and the min $\delta n_{\text{eff}} = 1.24 \times 10^{-4}$.

After the $\theta$ and $\beta$ have been determined, the bending loss of our proposed AT-AH-DC-FMF can be controlled by adjusting the radius of air holes, the width of air trenches and the refractive index of cladding. To guarantee our proposed AT-AH-DC-FMF working over the C and L band, according to ITU-T recommendations G. 654, the bending loss of the highest-order mode (LP$_{41}$) should be lower than 0.5 dB/100 turns (the bending radius $R = 30 \text{ mm}$) at 1625 nm [26]. In addition, the bending loss of the redundant mode (LP$_{22}$) ($R = 140 \text{ mm}$) should be greater than 1 dB/m at 1530 nm [26]. Before setting out to get proper parameters for satisfying the requirements of bending loss, it is necessary for us to figure out the influence of the parameters of air holes, cladding and the width of air trenches on $\Delta n_{\text{eff}}$, $\delta n_{\text{eff}}$. Therefore, the influence of $l$, $w$ and $\Delta n_2$ on the number of modes, min $\Delta n_{\text{eff}}$ and min $\delta n_{\text{eff}}$ are also explored in Fig. 4(a-c). Then the bending loss of AT-AH-DC-FMF as a function of the width of air trenches and the radius of air holes is investigated and the results are plotted in Fig. 4(d).
FIGURE 4. (a,b) The min Δn\text{eff} for adjacent LP modes and the min δn\text{eff} for adjacent spatial modes as a function of l and w at the wavelength of 1550 nm, respectively. (c) The influence of Δn\text{eff} on min Δn\text{eff} and the number of modes. (d) The bending loss of AT-AH-DC-FMF as a function of the width of air trenches and the radius of air holes.

Fig. 4(a,b) shows the min Δn\text{eff} for adjacent LP modes and the min δn\text{eff} for adjacent spatial modes as a function of l and w at the wavelength of 1550 nm, respectively. As can be seen from Fig. 4(a), the requirements of min Δn\text{eff} and min δn\text{eff} can be satisfied when l is larger than 1.6 μm, and the min Δn\text{eff} and min δn\text{eff} change slightly with the increase of l. In order to facilitate processing, we can choose l with a relatively larger value. Fig. 4(b) illustrates that the requirements of min Δn\text{eff} and min δn\text{eff} can be satisfied when w is ranging from 6.2 μm to 12.2 μm, and the min Δn\text{eff} and min δn\text{eff} change slightly with the increase of w. In Fig. 4(c), the number of modes can be increased with the increase of doping concentration. Five-modes fiber with min Δn\text{eff} = 1.98×10^{-3} can be realized when -0.5% ≤ Δn\text{eff} ≤ -0.1%. When Δn\text{eff} = -1.1%, 12 spatial modes are supported in our proposed AT-AH-DC-FMF.

FIGURE 5. The mode field distributions and electric field polarization directions of 12 spatial modes in our optimized AT-AH-DC-FMF at 1550 nm.

It is worth noting that in the core regions without air trenches around, its ability to bound light is weaker than that of the core regions with air trenches around, thus resulting in a little energy leakage into the cladding. But it does not affect the performance of our proposed AT-AH-DC-FMF.

IV. BIREFRINGENCE

Birefringence analysis of an optical fiber with an asymmetric refractive index distribution is necessary [5], [19]. Our proposed AT-AH-DC-FMF with asymmetrical air holes/trenches in the x and y axis, so that the residual thermal stress components in the x and y directions are different, which may result in birefringence through the elasto-optical effect. After the material constants such as the Yong’s modulus E, the Poisson’s ratio ν, the thermal expansion coefficients a and material density ρ are determined, the birefringence analysis can be conducted with the “Structural Mechanics Module” of COMSOL Multiphysics. α of GeO\textsubscript{2} and SiO\textsubscript{2} are 7.0×10^{-6} (1/K) and 5.4×10^{-5} (1/K), respectively. α of a doped material can be expressed by mixture model shown as α = (1−m)α\textsubscript{0} + mα\textsubscript{1} [27], where α\textsubscript{0} and α\textsubscript{1} are thermal expanding coefficient of the two kinds of dopants, 1−m and m denote the mole percentage of each dopant. The used elastic material parameters for modeling are calculated with the above method and listed in Table 1.
### TABLE 1

|                        | Cladding | Core | DC    |
|------------------------|----------|------|-------|
| Thermal expansion      | 5.4×10^{-7} | 1.01×10^{-6} | 0.93×10^{-6} |
| coefficient $\alpha$ (1/K) |          |      |       |
| Yong’s modulus $E$ (Pa) | 72.5×10^{9} | 68.26×10^{9} | 69.02×10^{9} |
| Poisson’s ratio $\nu$   | 0.17     | 0.137 | 0.14288 |
| Density $\rho$ (kg/m^3) | 2204     | 2244  | 2234  |
| First stress optical   | 6.5×10^{-13} |      |       |
| coefficient $B_1$ (Pa^1) |          |      |       |
| Second stress optical  | 4.2×10^{-13} |      |       |
| coefficient $B_2$ (Pa^1) |          |      |       |
| Drawing temperature $T_0$ (°C) | 1000    |      |       |
| Operating temperature $T_1$ (°C) | 20      |      |       |

**V. BROADBAND CHARACTERISTICS**

In this section, the performance of AT-AH-DC-FMF ($n_{\text{eff}}, \Delta n_{\text{eff}}, \delta n_{\text{eff}},$ chromatic dispersion $D$ and effective mode field area) covering the whole C and L band is investigated. The chromatic dispersion of AT-AH-DC-FMF is worth noting as it is a key factor resulting in optical pulse broadening. The chromatic dispersion $D$ is composed of material dispersion $D_m$ and waveguide dispersion $D_w$, both of which can be expressed as the following equations [13]:

$$D = D_m + D_w$$

(1)

$$D_m = -\frac{\lambda n_{\text{eff}}}{c} \frac{\partial n_{\text{eff}}}{\partial \lambda}$$

(2)

$$D_w = -\frac{\lambda n_{\text{eff}}}{c} \frac{\partial \epsilon}{\partial \lambda}$$

(3)

Where $c$ is the velocity of light in a vacuum, $\lambda$ is the wavelength of light, $n_{\text{eff}}$ is the refraction index of material as a function of $\lambda$, $Re(n_{\text{eff}})$ is the real part of the $n_{\text{eff}}$, respectively. The hybrid Sellmeier equation [29] is applied to calculate the refraction index of SiO$_2$ and GeO$_2$-SiO$_2$ at different wavelengths. The differential mode delay (DMD) that is crucial for reduction of power consumption and complexity of MIMO processing is defined as follows (take LP$_{11m}$ and LP$_{01}$ as an example) [13].

$$\text{DMD} = n_{\text{eff}} \Delta n_{\text{eff}}$$

(4)

The $n_{\text{eff}}, \Delta n_{\text{eff}}, \delta n_{\text{eff}},$ chromatic dispersion and effective mode field area ($A_{\text{eff}}$) as a function of wavelengths are calculated and represented in Fig. 7.
The effective refractive index, min $\Delta n_{\text{eff}}$ and min $\delta n_{\text{eff}}$ as functions of wavelengths are investigated in Fig. 7(a) and 7(b). As can be seen from Fig. 7(a), asymmetric air trenches lie closely to the core, which affects the symmetry of the mode fields and the effective index of guided modes directly, thus leading to the $n_{\text{eff}}$ of LP$_{12}$ and LP$_{41}$ is lower than the refraction index of cladding $n_{\text{cl}}$. But the AT and AH with enough size has the maximum refractive index difference to the core, exhibiting better capability in reducing the bending loss of higher-order LP modes and then transferring the leakage modes LP$_{12}$ and LP$_{41}$ into guided modes. In Fig. 7(b), the min $\Delta n_{\text{eff}}$ of LP modes is larger than $1 \times 10^{-3}$. In particular, as the min $\delta n_{\text{eff}}$ larger than $1 \times 10^{-4}$ over the whole C and L bands, the fourfold degenerate LP modes can be effectively separated into twofold modes, indicating our proposed AT-AH-DC-FMF has great potential to be applied to MIMO-less SDM. In Fig. 7(c), the chromatic dispersions of all modes (except LP$_{41}$) increase slightly from conventional band to long-wavelength band. The difference among chromatic dispersion of different modes main caused by waveguide dispersion. That is, due to the particularity geometric structure of our proposed few mode fiber, the transmission path of C-L band light pulse in the few mode fiber is different, which affects the effective refractive index of the mode, and the effective refractive index of LP$_{41}$ is the most affected. In the whole C and L band, the chromatic dispersion of all modes are lower than $60$ ps/nm/km, which does not affect the normal use of our proposed AT-AH-DC-FMF in short-distance transmission. Even if we want to achieve dispersion-free propagation, dispersion-compensation techniques can be employed [30]. Fig. 7(d) shows the $A_{\text{eff}}$ of spatial modes dependence on wavelengths. The $A_{\text{eff}}$ of all spatial modes (except LP$_{12s}$) are larger than $100 \ \mu$m$^2$ and the $A_{\text{eff}}$ of all spatial modes (except LP$_{41}$) slightly changes with wavelength. The broadband characteristics over a wide wavelength range of covering the whole C and L bands indicate the compatibility of our proposed AT-AH-DC-FMF with the mature WDM technique.

The performance of our depends on systematic variations of the fiber parameters that occur during the production process. So, we summarize the tolerance for $\Delta n_{\text{eff}}$ and $\delta n_{\text{eff}}$ of AT-AH-DC-FMF in Table 2. In this range, the effective index difference between the effective index difference between adjacent LP modes ($\Delta n_{\text{eff}}$) is larger than $1 \times 10^{-3}$ and the effective index difference between adjacent spatial modes ($\delta n_{\text{eff}}$) is larger than $1 \times 10^{-4}$, indicating that our proposed few mode fiber has enough device robustness. The optimal fiber performance of AT-AH-DC-FMF is exhibited in Table 3, and it can be seen in Table 3 that the bending loss of our proposed AT-AH-DC-FMF is lower than the bending loss in [5]. The confinement losses ($CL$) of all modes that are listed in Table 3 are calculated with the following formula [7]:

$$CL = \frac{40 \pi \text{Im}(n_{\text{eff}})}{\lambda \ln(10)}$$

where $\lambda$ is the free-space wavelength and $\text{Im}(n_{\text{eff}})$ is the imaginary part of the effective refractive index obtained by mode analysis.

**FIGURE 7.** The (a) $n_{\text{eff}}$, (b) min $\Delta n_{\text{eff}}$ and min $\delta n_{\text{eff}}$, (c) chromatic dispersions, and (d) $A_{\text{eff}}$ of spatial modes as functions of wavelengths over the whole C and L band.

**TABLE 2**

| r(μm) | $\Delta n$(%) | $\delta n$(%) | $\theta$(deg) | $\beta$(deg) | $l$(μm) |
|-------|----------------|---------------|--------------|--------------|---------|
| 8.8   | -1.0 to -      | 0.6 to        | -1.5 to -    | 86 to        | 31 to   |
|       | 0.1            | 1.6           | 1.1          | 102          | 40      | >1.6    |

**TABLE 3**

| Fiber properties | Fiber performances |
|------------------|--------------------|
| $n_{\text{eff}}$ | 1.45348 (LP$_{10}$), 1.451411 (LP$_{11}$), 1.451287 (LP$_{12}$), 1.448868 (LP$_{21}$), 1.44829 (LP$_{22}$), 1.44726 (LP$_{23}$) |
| $\Delta n_{\text{eff}}$ for spatial modes | 1.24 × 10$^{-4}$ |
| $\delta n_{\text{eff}}$ for LP modes | 1.03 × 10$^{-5}$ |
| $A_{\text{eff}}$ (μm$^2$) | 131.2 (LP$_{10}$), 118.5 (LP$_{11}$), 116.9 (LP$_{12}$), 120.4 (LP$_{21}$), 103.6 (LP$_{22}$), 122.5 (LP$_{23}$), 111.8 (LP$_{31}$), 108 (LP$_{32}$), 93.4 (LP$_{33}$), 136.3 (LP$_{41}$), 129.6 (LP$_{42}$) |
Through this method, the structures for manufacturing triangular-hole photonic fiber can be achieved with the help of AT and DC. The AT and AH plays an important role in helping the bending loss of AT-AH-DC-FMF be compatible with mature WDM technology, thus further enabling optical communication capacity and simplifying the system complexity.

VI. RECOMMENDATIONS FOR FABRICATION

Selecting an appropriate fabricating method can improve the probability of success during fiber fabrication. D. Chen et al. [31] used uniform air holes to form different basic cell structures for manufacturing triangular-hole photonic crystal fiber (PCF) and rectangular-hole PCF in practice, which provided an idea for manufacturing the AT in our proposed AT-AH-DC-FMF. Through this method, the structural distortion can be minimized during fabricating fiber with different shaped holes. According to mature technology in fabricating hole-assisted fibers [32], we believe the Stack-And-Draw technique is one of the ways that are suitable for the fabrication of our proposed AT-AH-DC-FMF. There are three steps that need to be followed to manufacture the AT-AH-DC-FMF. Firstly, some glass capillaries and glass rods are used to form AT and cladding. Secondly, 6% and 7.3% mole fraction of GeO2 are needed to dope in SiO2 to form the DC and core. Finally, our optimized AT-AH-DC-FMF can be manufactured after the melting and drawing process. The low doping during the manufacturing of DC and core indicates a relatively simpler fabrication process of our proposed AT-AH-DC-FMF than common elliptical core fibers and PMF. There is another method to fabricate our proposed AT-AH-DC-FMF. The main processes are as follows: firstly, fabricating a step-index fiber core preform with a circular pure SiO2 cladding by utilizing the normal MCVD technology; secondly, drilling the uniform air holes in particular positions of our fabricated preform to form the preform of our proposed AT-AH-DC-FMF; finally, our proposed few mode fiber can be fabricated after the drawing process. Previous study [33] provides us a method of filling nitrogen gas in the uniform air holes to against the ambient pressure, thus stopping the holes collapse during the fiber drawing. The discussion in this section proved that the design scheme of our proposed AT-AH-DC-FMF is feasible.

VII. CONCLUSION

In this paper, an AT-AH-DC-FMF features some asymmetrical air trenches, air holes and a depressed step-index core, supporting 12 spatial modes is proposed for MIMO-less SDM. The fiber performance dependence on the parameters of DC, AT and AH are investigated with FEM. According to our simulation results, the minimum $\Delta n_{\text{eff}}$ of greater than $1.03 \times 10^{-3}$ and minimum $\delta n_{\text{eff}}$ of greater than $1.24 \times 10^{-4}$ can be achieved with the help of AT and DC. The AT and AH plays an important role in helping the bending loss of AT-AH-DC-FMF satisfying the ITU-T recommendations of G. 654. Our proposed AT-AH-DC-FMF shows small birefringence effect and it is feasible to be fabricated with the Stack-And-Draw technique. In addition, stable comprehensive broadband characteristics such as small chromatic dispersion, large $\Delta n_{\text{eff}}$, large $\delta n_{\text{eff}}$ and large effective mode area over the whole C and L band provide an opportunity for the MIMO-less SDM based on AT-AH-DC-FMF to be compatible with mature WDM technology, thus further enabling optical communication capacity and simplifying the system complexity.

REFERENCES

[1] Tongxin Yang, Hu Zhang, Lixia Xi, Qiankun Li, Xiaoguang Zhang, Xiaojian Wang, Wenbo Zhang, Xianfeng Tang, "Design of 18-mode hole-assisted elliptical-core polarization-maintaining few-mode fiber," Optics Communications, Volume 507, 127647, ISSN 0030-4018, 2022.

[2] ISSN 0030-4018, Jiajia Zhao, Ming Yang, Kyungwhan Oh, Zhenhua Feng, Can Zhao, Ruolin Liao, Songjian Fu, Perry Ping Shum, and Deming Liu, "Polarization-maintaining few mode fiber composed of a central circular-hole and an elliptical-ring core," Photon. Res. 5, 261-266 (2017).

[3] P. Sillard, D. Molin, M. Bigot-Astruc, H. Maerten, D. Van Ras, and F. Achten, "Low-DMGD 6-LP-Mode Fiber," in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2014), paper M3F.2.

[4] J. Zhang et al., "A Weakly-Coupled Few-Mode Optical Fiber With a Graded Concave High-Index-Ring," in IEEE Photonics Journal, vol. 13, no. 2, pp. 1-10, April 2021, Art no. 7200710.

[5] Yuheng Xie, Li Pei, Jinghong Zheng, Qi Zhao, Tingan Ning, and Jing Li, "Design of steering wheel-type ring depressed-core 10-mode fiber with fully improved mode spacing," Opt. Express 29, 15067-15077 (2021).

[6] S. Jiang et al., "Design and Characterization of Ring-Assisted Few-Mode Fibers for Weakly Coupled Mode-Division Multiplexing Transmission," in Journal of Lightwave Technology, vol. 36, no. 23, pp. 5547-5555, 1 Dec. 1, 2018.

[7] Miaofang Zhou, Huajun Yang, Qiankun Li, Xiaoguang Zhang, Xiaojian Wang, Wenbo Zhang, Xianfeng Tang, "Design and analysis of hollow core Bragg fibers array for space division multiplexing," Results in Physics, Volume 30, 104877, ISSN 2211-3797, 2021.

[8] Weijun Song, Hongyao Chen, Jianping Wang, Changling Liu, Yijin He, Zhenzheng Li, Mei Liu, "Panda type elliptical ring core few-mode fiber," Optical Fiber Technology, Volume 60, 102361, ISSN 261-266 (2017).

[9] Seongjin Hong, Kyoungyeon Choi, Yong Soo Lee, and Kyunghwan Oh, "Two-mode Fiber with a Reduced Mode Overlap for Uncoupled Mode-division Multiplexing in C+L Band," Curr. Opt. Photon. 2, 15067-15077 (2021).

[10] F. Achten, "Low-DMGD 6-LP-Mode Fiber," in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2014), paper M3F.2.

[11] J. Zhang et al., "A Weakly-Coupled Few-Mode Optical Fiber With a Graded Concave High-Index-Ring," in IEEE Photonics Journal, vol. 13, no. 2, pp. 1-10, April 2021, Art no. 7200710.

[12] Yuheng Xie, Li Pei, Jinghong Zheng, Qi Zhao, Tingan Ning, and Jing Li, "Design of steering wheel-type ring depressed-core 10-mode fiber with fully improved mode spacing," Opt. Express 29, 15067-15077 (2021).

[13] S. Jiang et al., "Design and Characterization of Ring-Assisted Few-Mode Fibers for Weakly Coupled Mode-Division Multiplexing Transmission," in Journal of Lightwave Technology, vol. 36, no. 23, pp. 5547-5555, 1 Dec. 1, 2018.
[11] Y. Jung et al., "Low-Loss 25.3 km Few-Mode Ring-Core Fiber for Mode-Division Multiplexed Transmission," in Journal of Lightwave Technology, vol. 35, no. 8, pp. 1363-1368, 15 April 15, 2017.

[12] H. Zhang, J. Zhao, Z. Yang, G. Peng and Z. Di, "Low-DMGD, Large-Effective-Active Area and Low-Bending-Loss 12-LP-Mode Fiber for Mode-Division-Multiplexing," in IEEE Photonics Technology, vol. 11, no. 4, pp. 1-8, Aug. 2019.

[13] Yanlei Li, Xiao Wang, Hongjun Zheng, Xin Li, Chenglin Bai, Weisheng Hu, Yang Liu, Qiujuan Dong, "A novel six-core few-mode fiber with low loss and low crosstalk," Optical Fiber Technology, Volume 57, 102211, ISSN 1068-5200, 2020.

[14] S. Fu et al., "Panda Type Few-Mode Fiber Capable of Both Mode Profile and Polarization Maintenance," in Journal of Lightwave Technology, vol. 36, no. 24, pp. 5780-5785, 15 Dec. 15, 2018.

[15] Haozhe Yan, Shangyuan Li, Zhengyang Xie, Xiaoping Zheng, Hanzi Zhang, and Bingkun Zhou, "Design of Panda-Mode Fiber with 10 polarization-maintaining modes," Photon. Res. 5, 1-5 (2017).

[16] R. Maruyama, N. Kuwaki, S. Matsuo and M. Ohashi, "Relationship between stress-induced birefringence and mode multiplexing," Applied Optics, Volume 33, Issue 11, pp. 5611-5616, 1994.

[17] P. Sillard, M. Bigot-Astruc and D. Molin, "Few-Mode Fibers for Mode-Division-Multiplexed Systems," in Journal of Lightwave Technology, vol. 39, no. 12, pp. 4028-4033, 15 June 15, 2021, doi: 10.1109/JLT.2020.3022104.

[18] J. Zhao, B. Li, M. Tang, S. Fu, S. Liu, P. P. Shum, and D. Liu, "Design and analysis of hole-assisted few mode fiber with ultra-low differential mode group delay (DMGD)," in Asia Communications and Photonics Conference 2015, C. Lu, J. Luo, Y. Ji, K. Kitayama, P. Jiang and opto, "Highly elliptical core fiber with stress-induced birefringence for mode multiplexing," Opt. Lett. 45, 2822-2825 (2020).

[19] J. Zhao, B. Li, M. Tang, S. Fu, S. Liu, P. P. Shum, and D. Liu, "Design and analysis of hole-assisted few mode fiber with ultra-low differential mode group delay (DMGD)," in Asia Communications and Photonics Conference 2015, C. Lu, J. Luo, Y. Ji, K. Kitayama, P. Jiang and opto, "Highly elliptical core fiber with stress-induced birefringence for mode multiplexing," Opt. Lett. 45, 2822-2825 (2020).

[20] A. Corsi, Jun Ho Chang, Ruohui Wang, Lixian Wang, Alessandro Corsi, Jun Ho Chang, Ruohui Wang, Lixian Wang, A. Corsi, Jun Ho Chang, Ruohui Wang, Lixian Wang, A. Corsi, Jun Ho Chang, Ruohui Wang, Lixian Wang, A. Corsi, Jun Ho Chang, Ruohui Wang, Lixian Wang, "Low-DMD and low-crosstalk few-mode multi-core fiber with air-trench/holes assisted graded-index profile," Optics Communications, Volume 474, 126155, ISSN 0030-4018, 2020.

[21] Hanyi Zhang, and Bingkun Zhou, "Design of PANDA ring-core fiber with 10 polarization-maintaining modes," Photon. Res. 5, 1-5 (2017).

[22] M. Kasahara et al., "Design of Three-Spatial-Mode Ring-Core Fiber," in Journal of Lightwave Technology, vol. 32, no. 7, pp. 1337-1343, April 11, 2014.

[23] Shi Chen and Jian Wang, "Design of PANDA-type elliptical-core multimode fiber supporting 24 fully lifted eigenmodes," Opt. Lett. 43(15), 3718–3721 (2018).

[24] Sheng Liu, "Design and Characterization of Nanopore-Assisted Weakly-Coupled Few-Mode Fiber for Simpler MIMO Space Division Multiplexing," in IEEE Access, vol. 8, pp. 76173-76181, 2020.

[25] Weisheng Hu, Yang Liu, Qiuhuan Dong, "A novel six-core few-mode fiber with low loss and low crosstalk," Optical Fiber Technology, Volume 57, 102211, ISSN 1068-5200, 2020.

[26] Rongfeng Guan, Fulong Zhu, Zhiyin Gan, Dexiu Huang, Sheng Liu, "Stress birefringence analysis of polarization maintaining optical fibers," Optical Fiber Technology, Volume 11, Issue 3, 2005, Pages 240-254, ISSN 1068-5200.

[27] Yuehua Li, B. M. A. Rahman, and K. T. V. Grattan, "Thermal-stress-induced birefringence in bow-tie optical fibers," Appl. Opt. 33, 5611-5616 (1994).

[28] James W. Fleming, "Dispersion in GeO2–SiO2 glasses," Appl. Opt. 23(24), 4486–4493 (1984).

[29] R. Noc et al., "Dispersion in GeO2–SiO2 glasses," Appl. Opt. 23(24), 4486–4493 (1984).

[30] Yifan Zheng, was born in Hunan, China, in 1996. She is currently pursuing a Ph.D. degree at the University of Electronic Science and Technology of China. Her current research interests include few-mode fiber design, multi-core fiber design, optical design, and free space optical communication.

[31] Ping Jiang, was born in Sichuan, China. She is currently an Associate Professor at the University of Electronic Science and Technology of China. Her current research interests include free space optical communication, optical design, and photonic crystal fiber design.

[32] Weina Caiyang, was born in Yunnan, China. He is currently a Post-doctoral at the University of Electronic Science and Technology of China. His current research interests include omnidirectionally-emitting laser, free space optical communication, and optical design.

[33] Yan Qin, was born in Shaxi, China. She is currently pursuing a Ph.D. degree at the University of Electronic Science and Technology of China. Her current research interests include photonic crystal fiber design, vortex beam, turbulent atmosphere, and free space optical communication.

[34] Yifan Zheng, was born in Shaxi, China. She is currently pursuing a Ph.D. degree at the University of Electronic Science and Technology of China. Her current research interests include free space optical communication and optical design.