Evolutionary Design of Single-Mode Microstructured Polymer Optical Fibres using an Artificial Embryogeny Representation

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ABSTRACT
Polymer microstructured optical fibres are a relatively recent development in optical fibre technology, supporting a wide variety of microstructure fibre geometries, when compared to the more commonly used silica. In order to meet the automated design requirements for such complex fibres, a representation was developed which can describe radially symmetric microstructured fibres of different complexities; from simple hexagonal designs with very few holes, to large arrays of hundreds of holes. This representation uses an embryogeny, where the complex phenotype is 'grown' from a simpler genotype, and the resulting complexity is primarily a feature of the reuse of gene elements that describe the microstructure elements. Most importantly, the growth process results in the automatic satisfaction of manufacturing constraints. In conjunction with a multi-objective genetic algorithm, this formed a robust algorithm for the design of microstructured fibres for particular applications of interest. In this paper the algorithm is used to design one of the most common types of microstructured fibres – single-moded fibres. Various types of single-moded designs that have not been encountered in the literature were discovered, identifying new 'design themes'. One of the designs was subsequently manufactured, the details of which are included.

Categories and Subject Descriptors
I.2.1 [**Artifical Intelligence**]: Applications and Expert Systems, *Medicine and science.*

General Terms
Algorithms.

Keywords
Microstructured optical fibre, polymer optical fibre, single-mode fibre, optical design, artificial embryogeny, representation.

1. INTRODUCTION
Optical fibres are nowadays used in applications ranging from long distance telecommunications, short distance high bandwidth networks, 'photonic microchips', sensing, and medical diagnosis. Standard fibres contain a solid internal structure, usually doped with chemicals, to aid in the confinement of light and tailoring of the light propagation properties. The development of silica microstructured optical fibres has expanded the application areas of optical fibres. The inclusion of air holes results in highly tailorable optical properties not possible in traditional fibres, where the arrangement of air holes helps confine the light within the fibre.

Silica microstructured fibres [3] primarily have hexagonal arrays of holes, a result of the capillary stacking approach used to manufacture preforms. Microstructured polymer optical fibres (MPOF) [11] are a more recent advance, opening up the design space considerably. To reflect this, new search and design algorithms need to be developed which can generate the required diversity of designs and, in parallel, deal with manufacturing constraints.

This paper presents a genetic algorithm (GA) which uses an *embryogeny*, or a *growth phase* to convert a design from its genotype to the microstructured optical fibre (phenotype). The result is a compact binary representation which can generate microstructured fibre designs, where the number of holes and the overall complexity of the designs is not predetermined, but can evolve over time. A brief overview of microstructured fibre design is presented in Section 2. Representations and embryogenies in GAs are then introduced in Section 3, followed by a short overview of MPOF manufacture in Section 4. Details of the representation and embryogeny for microstructured fibres are given in Section 5, along with a discussion of symmetry in Section 6. The genetic operators are discussed in Section 7, followed by the population operators in Section 8. Finally, Section 9 describes the successful real world application of the algorithm on the design of single-mode microstructure optical fibres, along with the manufacture of an optimal single-mode fibre.

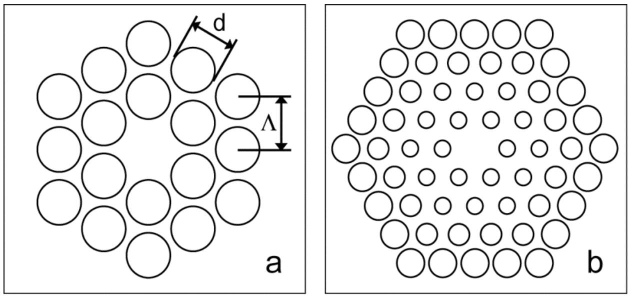


Figure 1. Two types of microstructured optical fibre profiles that have been used in GA optimisation in the literature. a is from [7] and b is from [9].

2. PREVIOUS REPRESENTATIONS FOR MICROSTRUCTURED FIBRE DESIGN

The design of microstructured fibres has to date mainly been a human-driven process of analysis, where optical properties such as single-modedness, high-nonlinearity and dispersion are considered. Examples of optimisation in the literature have mainly focussed on the simple structures which can be parameterised in terms of values such as Λ, d [7] (Figure 1a). Extensions of this design space to multiple rings with different sized holes have also been published [9] (Figure 1b), with fitness functions involving more complex optimal properties such as dispersion flattening. Since the designs can be described in terms of a simple parameterisation, it is straightforward to envisage all possible designs. Allowing both the symmetry and hole properties to change however, increases the range of possible designs.

With the development of new manufacturing techniques to produce Microstructured Polymer Optical Fibres (MPOF) [11], designs of almost arbitrary hole arrangements are possible. For example, Figure 2E is a simple square hole array MPOF, and Figure 2F is a far more complicated MPOF with 171 holes using 4 different hole sizes. Given this flexibility, more interesting design questions can be posed. Rather than focussing on optimising the sizes of holes in a hexagonal array with a fixed number of rings, one can ask "what is the best symmetry for this sort of design?", or "can we achieve these properties with fewer holes?". Given the huge design space of symmetries and hole arrangements that can be explored, an automated design algorithm would need to be able to evolve designs which can change symmetry and their complexity (for example, overall number of holes) over time.

3. REPRESENTATIONS

Fundamental to a GA is the genetic representation, which is used to store details of the design. Simple representations are generally fixed in length, resulting in designs which are variations of a pre-defined *design type*. However, appropriate representations can be developed which encode the topology, complexity and other large scale features, allowing the overall design to change over time.

3.1 Embryogenies

Typically in a GA the conversion from genotype to phenotype is quite direct, for example converting a binary genotype to numerical values. An *embryogeny* refers to a conversion where the genotype is used as an encoded set of 'instructions', which are used to grow or develop the phenotype. This is a characteristic of developmental systems found in nature, resulting in the complexity of the phenotype being greater than the underlying genotype. Some examples of symmetric phenotypes found in nature are shown in Figures 2A-C. Two of the main features of these sorts of systems are:

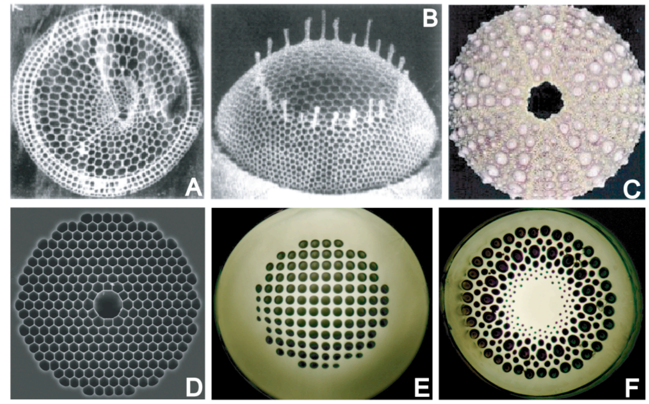


Figure 2. Examples of symmetric structures found in nature and microstructured optical fibre structures. A and B are *radiolarians*. C is the common sea urchin, which exhibits 5-fold radial symmetry. D is a hexagonal silica microstructure fibre. E and F are polymer microstructure fibres. E is a square array of holes used for medical imaging, and F is a more complex design for high bandwidth communications with a radial symmetry of 18.

1. **Indirect correspondence between features of the genotype and phenotypic features**. The genotype acts as a set of instructions to grow or develop designs,
2. **Polygeny**. Phenotypic characteristics of designs are not dependent on just one part of the genotype, but can arise from the effects of multiple genes acting in combination.

Embryogenies offer many advantages over simple representations for the design of complex objects such as microstructured fibres. Using a direct representation, the location and size of every single hole in a microstructured fibre would have to be described. As more holes are defined in the genotype, the search becomes less efficient, especially since many of the genes will interact when considering manufacturing constraints, such as the minimum allowed distance between holes.

Embryogenies can also exploit hierarchy to re-use parts of the genotype, for example, sets of holes which reappear at different locations in the structure. This results in a more efficient, and lower-dimensional search space. Symmetry is particularly relevant in microstructured fibre design since rotational symmetry, or repeating patterns, are common in fibre designs. If one imagines all the symmetries and hole arrangements possible for microstructured fibres, the phenotypic space is massive.

In converting from the compact genotype to extended phenotype, embryogenies employ a process, or a set of instructions. These instructions can be intrinsic to the representation, where they are defined within the genotype. They can also be extrinsic or even external [4], where an external algorithm is used as a set of instructions to develop the phenotype according to values defined by the genotype.

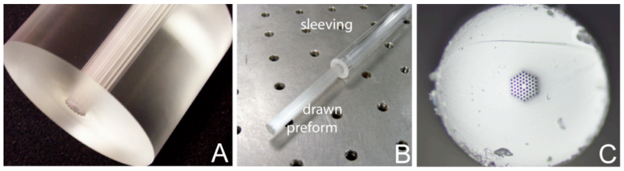


Figure 3. Three stages of MPOF manufacture.

3.2 Constraints

Since the conversion from genotype to phenotype is now a process, rules can be built into this algorithm which can ensure that the genotype will produce valid designs. The embryogeny is important here, since in the case of a more direct representation, the interactions between the multiple genes would result in many complex constraints that would be difficult or impossible to satisfy. For example, a direct representation encoding n holes would require the simultaneous satisfaction of $n(n-1)/2$ combinations of constraints, adding to the complexity of the search space.

3.3 Drawbacks

Although embryogenies are powerful representations for complex designs, there are drawbacks. Embryogenies, along with the corresponding mutation and recombination operators, are often hand designed, since there are no set rules or methodologies on how to design an embryogeny. The representations themselves can also evolve [10]. Some simple criteria can be used to evaluate the effectiveness of an embryogeny, such as testing them on simpler problems to discover if they behave in an appropriate way. For example, multiple runs of the GA using different random starting conditions should yield very similar optimal designs. Further details of this in relation to the GA presented here are available in [6].

4. AN OVERVIEW OF MPOF MANUFACTURE

Before discussing a representation for microstructured optical fibres, the process of MPOF manufacture needs to be considered. The manufacturing method most often used to prepare preforms at the Optical Fibre Technology Centre is drilling. Holes are drilled into a poly-methyl methacrylate (PMMA) preform approximately 75 mm in diameter and 70 mm long using a computer controlled mill (Figure 3A). A limited set of drills are available, resulting in a discrete set of hole sizes. A commonly used set are [1.2, 1.5, 2.0, 3.0, 4.5, 6.0, 7.0, 8.5] mm. This results in the first important manufacturing constraint - that only particular hole sizes are available. The second manufacturing constraint is the minimum distance between holes when the preform is drilled, which is required to help prevent wall collapse or fracturing. Typically 0.2 to 0.5 mm is sufficient.

The preform is then heated, and drawn to a cane, usually 5 to 10 mm in diameter (Figure 3B). This can then be sleeved with more PMMA, and then undergoes a further draw to produce an optical fibre of diameter 200 μm to 1000 μm in diameter (Figure 3C). This results in a size reduction ranging from 300 to 1000 times compared to the original preform. A reduction of 340 times would result in 1.2mm holes having an in-fibre diameter of 3.5μm. Holes can change both their relative size and shape during drawing [13]. These deformations depend on the draw conditions (temperature for example), but also depend on the proximity and size of surrounding holes. For simplicity however, we presume that holes are undeformed during the draw process.

5. A REPRESENTATION FOR MICROSTRUCTURED OPTICAL FIBRES

Representations express how a phenotype is encoded as a genotype. The representation consists of two major parts: the genotype, which encodes the details associated with the design, and the embryogeny, which is the algorithm that converts from genotype to phenotype. The genotype used here defines two major features of the microstructured fibre, the positions and sizes of a variable number of air holes, and the rotational symmetry of the structure. The embryogeny is then used to convert the genotype into a valid microstructured fibre design, ensuring that manufacturing constraints such as non-overlapping holes, are maintained. In developing the representation, two main factors were considered:

1. Exploitation of radial symmetry to minimise the length of the genotype, but simultaneously ensure the design of symmetric microstructured fibres,

2. The direct incorporation of constraints into the embryogeny, for example, discrete, rather than continuous sizes of holes, and other manufacturing constraints such as the minimum allowed distance between holes.

Each part of the representation will now be explored in detail.

5.1 Genotype

The genotype is used to store

- An integer value which represents the global rotational symmetry of the microstructured fibre n_{symm},
- The position and size of each hole x_i, y_i, r_i where $i \in [1, \ldots, n_h]$ and n_h is the number of holes in a sector.

Only the details of holes in one repeating unit of the designs are stored, so that the total number of holes encoded by the genotype is $n_h\ n_{symm}$. The fibres considered here are made out of polymer, and the holes all contain air, so no information about the materials needs to be explicitly defined in the genotype (although this can be added for more complex designs). The position values x_i, y_i are decimal values encoded in binary form. r_i is an integer which represents a discrete hole size due to the limited availability of hole sizes used in the drilling preparation of the MPOF preform.

The above values are individually represented in binary form, and concatenated into a single binary string. Thus, existing mutation and recombination operators for the cutting and splicing of binary strings can be used.

The bit length of n_{symm} is b_s, the x_i,y_i values have equal length $b_{x,y}$ and the hole size value has length b_r. The total genotype length b_t, is

$$b_t = b_s + n_h\,(2\,b_{x,y} + b_r)$$

This relationship encapsulates the variable length of the genotype. Holes which are represented by a binary string of length $2b_{x,y}+ b_r$ can be added to or deleted from the genotype, whilst still maintaining a length which satisfies the above equation.

5.2 Embryogeny

The conversion of the binary genotype to a valid phenotype involves 4 steps, the decoding of the binary genotype to its

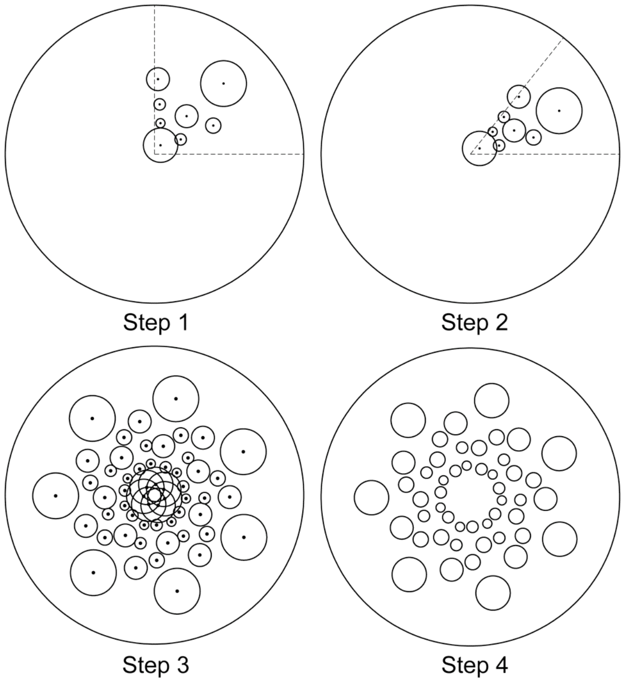
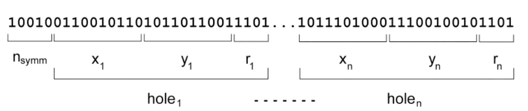


Figure 4. Genotype to phenotype conversion of a microstructured optical fibre as detailed in the text.

numerical values, and then the development of the radially symmetrical design.

Step 1. Decoding the binary genotype

The first phase of the genotype to phenotype mapping involves decoding the genotype into the numerical values it represents. The first b_s bits are decoded into an integer representing the symmetry n_{symm}.



A different number of bits can be used to represent different upper limits on the symmetry. A typical value used is b_s=5 resulting in a maximum symmetry of $n_{symm}=2\text{^}b_s-1=31$.

The n_h holes are then decoded into their positions and hole sizes. The cartesian position values x_i,y_i are decoded into unsigned decimal values, thus, lying in the first quadrant and easily generating an n_{symm}=4 symmetry. As an example, if $b_{x,y}$=9, where the first 6 bits represent the whole component and the remaining 3 bits represent the fractional component, this would result in a minimum increment of 0.125 μm and a maximum value of 63.875 μm. Larger x_i,y_i values can be achieved by increasing $b_{x,y}$ or by scaling the values of x_i,y_i.

The mapping of the r_i values to hole sizes is treated a little differently. Since only particular hole sizes (drill bits) are available for use, the r_i binary string is converted into an integer value. The different integer values map to the hole sizes which are available. A choice of b_r=3 specifies 8 different hole sizes. These decoded positions form the basic n_{symm}=4 structure, an example of which is shown in Figure 4, Step 1.

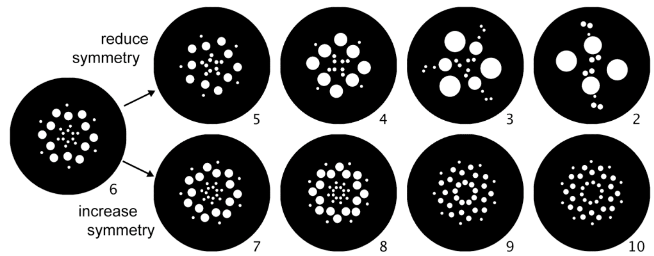


Figure 5. A microstructured optical fibre which has been converted to various symmetries. On the top row it is reduced from 6 to 2, and on the bottom increased from 6 to 10 (note that higher symmetries are possible).

Steps 2 and 3. Converting to a Symmeterised Fibre.

The basic decoded structure initially corresponds to the correct n_{symm}=4 (Figure 4, Step 1). The next step is to transform this structure symmetry. The polar r_i, θ_i coordinates are evaluated for each hole, and then the angles are transformed as

$$\theta_i = 4 / (n_{symm}\ \theta_i);\ i \in [1,...,n_h]$$

An example is shown in Step 2 in Figure 4 for n_{symm}=7. This group of holes, referred to as the *unit holes*, are then copied radially n_{symm}-1 times in steps of $\theta = 2\pi/n_{symm}$, resulting in the complete symmeterised microstructured fibre as shown in Step 3.

Step 4. Growing the Microstructured Fibre.

From Figure 4, Step 3, the holes are initially overlapping or touching after being converted into a complete symmetrical structure. This final stage of the embryogeny involves 'growing' the size (radii) of the holes in order to obey manufacturing constraints. More specifically, each hole must be surrounded by a minimum wall thickness w_h for structural stability.

The two main ideas behind the algorithm are:

- The algorithm steps through the available hole sizes, until holes either equal their own maximum defined size r_i, or begin to overlap with neighbouring holes,
- When holes stop growing, the growth of corresponding holes in the other symmetrical units is also stopped in parallel to ensure a symmetrical fibre.

The algorithm is outlined in detail in [6]. This results in Figure 4, Step 4, with all holes at least w_h apart. Some of the holes have achieved their genotype size, whereas others are smaller due to the presence of surrounding holes. The holes in the centre have not been expressed phenotypically at all because of their close proximity to one another.

The growth process which results in the Step 4 design can be seen as a 'correction' to the phenotype from Step 3, forming a *legal mapping* [14]. Since all individuals are phenotypically correct with respect to constraints, the overall performance of the GA is high since no effort is wasted on infeasible solutions that must be removed through penalty approaches or other methods.

The phenotypic hole sizes are not propagated back into the genotype. The genotype serves the purpose of specifying a 'potential' hole size, then the surrounding phenotypic features and the genotype itself govern the extent to which holes can grow. Thus, any genotype, even a random string of binary values, is a feasible design. A number of phenotypes (fibres) from randomly generated binary strings are shown in Figure 6.

A phenotypic feature that cannot occur as a result of the algorithm is a central air hole. This can be included by adding a binary string of length b_r, representing the size of a hole at the origin. The size of the hole would be influenced by the surrounding holes, or a decoded size value of 0 could specify a zero hole radius. The symmetry copying operation would not be applied to this hole, thus the global n_{symm} symmetry would still be maintained.

6. SYMMETRY

Figure 5 shows an example of a design where the binary part of the genotype describing the holes x_i,y_i remain constant, but the symmetry is varied n_{symm}=2,3,…,10. Designs with n_{symm}=0 could be used to represent circularly symmetric fibres, and n_{symm}=1 for random arrangements of holes. However, neither of these two cases are of interest in the real problems discussed here, thus, values of 0 or 1 are mapped to n_{symm}=2. Limiting the representation to designs which exhibit rotational symmetry of at least 2 is important for various reasons, which are discussed below.

The first is related to the computational evaluation of the properties of fibres. The evaluation of modes in random structures is the most computationally demanding case. Any symmetry in the design can be exploited to reduce the computational effort required, such that only a slice of angular width 2π n_{symm} needs to be evaluated [2]. Secondly, symmetry is important in the drawing of the fibre. Hole deformations occur during fibre drawing, and the types of and extent of deformations relate strongly to the surrounding holes [13]. Any digression from a symmetric pattern of holes can cause larger deformations to occur. Thirdly, symmetry can help control and tune optical effects. Designs with random hole arrangements have been published [8], where the optical effects achieved in these fibres are typically a result of homogenisation effects which are relatively robust with respect to perturbations introduced during manufacture. Not all optical properties however are robust to such perturbations. Finally, as discussed, using symmetry to repeat the defined patterns of holes reduces the dimensionality of the search space.

7. GENETIC OPERATORS

Associated with a representation are the genetic operators: the recombination of genotypes from different individuals to create new designs, and mutation, to modify existing genotypes.

7.1 Initialisation

Initialisation involves the generation of binary strings of length b_s+n_h(2$b_{x,y}$+b_r) to seed the population. For each individual, a random value of n_h is used, typically $n_h \in [1,15]$, to generate individuals with different numbers of holes. The genotype of length b_t is then filled with random binary values. In some cases pre-defined fibres can be used to seed the population, but generally the GA is seeded using a completely random population.

7.2 Recombination

The population generally consists of a group of designs which vary in the genotype length, and the recombination operator must deal with recombining individuals of different lengths and also

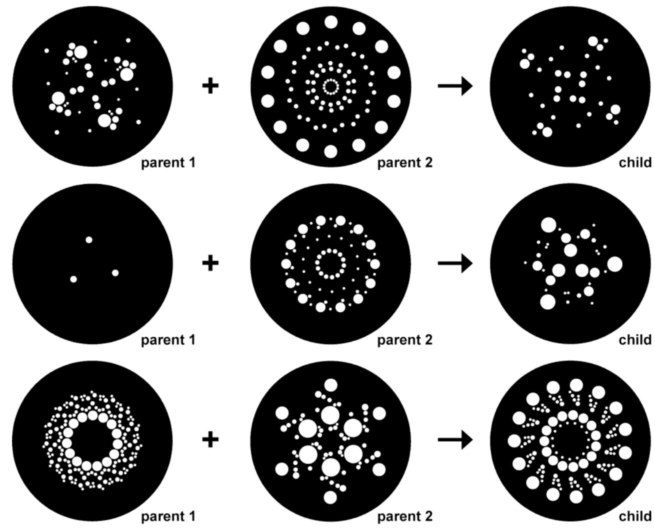
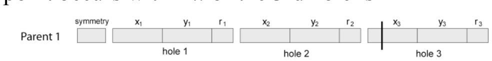


Figure 6. Three examples of single child recombination from two randomly generated parents with different lengths. The inheritance of features such as symmetry, groups of holes and single holes can be seen.

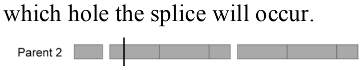
producing children with valid genotype lengths. The result is that limitations are placed on where splicing takes place during variable length crossover to maintain valid genotypes.

Single point crossover between two parents is used to produce one or two children. The breeding pairs are typically chosen using $k=2$ tournament selection, denoted parent 1 and parent 2.

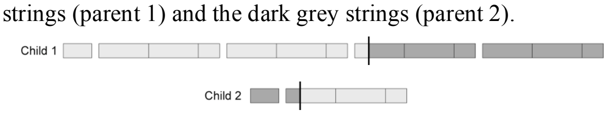
Given parent 1 with binary length $b_{t,1}$, a random splice point is chosen in the range [1,$b_{t,1}$]. This splice point can sit within n_{symm}, on the edge of binary strings representing holes or within those binary strings themselves. An example with 3 holes, where the splice point occurs within x of the 3rd hole is



In order for the child's genotype to have a valid length, the recombination point on the 2nd parent must be chosen at the same point within the n_{symm} or x_i, y_i, r_i binary substring. Given parent 2 with $n_{h,2}$ holes, a random integer in the range [1, $n_{h,2}$] is generated which picks which hole the splice will occur.



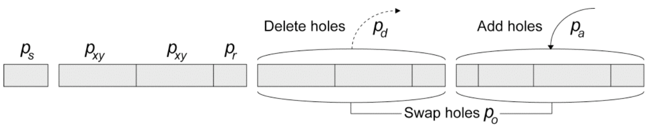
The exact cut position within the parent 2 binary string depends on the cut point selected for parent 1 in order to maintain the correct length. Once these splice points have been defined, one, or two children, can be generated by joining the light grey binary strings (parent 1) and the dark grey strings (parent 2).



From two parents with 3 and 2 holes, children with 4 holes and a single hole were generated. Thus, the complexity of designs is able to change. Typically the GA only retains one of the two children. In the case where pure elitist survival selection is used, more parents have the opportunity to breed and contribute genetic material to the child population, resulting in more diverse child population. Examples of the phenotypes of recombined individuals are shown in Figure 6. Although the genotype and corresponding recombination operators are very simple, the resulting phenotypic behaviour of individuals that are recombined is quite complex.

7.3 Mutation

Two types of mutation operators are used. One operates on individual bits, and other operates on whole substrings at a time.



Different mutation rates are used on different parts of the genotype. A mutation rate p_s is used for the bits representing the symmetry value. The rate $p_{x,y}$ is used for the bits representing the position values, and the rate p_r for the hole size values.

Higher level hierarchical operators are used which can add and delete complete holes from the genotype, increasing or decreasing the total number of holes. The mutation rate p_a is associated with the rate of hole addition, where a random string of length $2b_{x,y}+b_r$ is spliced onto the genotype. Binary segments can also be deleted at a rate of p_d, where a random hole is chosen for deletion. Since single point crossover tends to recombine holes which lie far apart within the genotype, another operator randomly selects two holes in a genotype and swaps their positions. This occurs at a rate p_o. Note that changing the ordering of holes in the genotype has no effect on the phenotype.

8. POPULATION OPERATORS

Population operators include selection for survival and selection for breeding. In selecting which individuals survive from one generation to the next, a pure elitist scheme is used, such that both parents and children have the opportunity to survive. The population of size N_p+N_c is ordered from best to worse in terms of the individual fitness values, and the top N_p designs survive. In the case of multiple objectives, the NSGA-II Pareto ranking and distance measures [1] are used to completely order the population. In choosing individuals for breeding, $k=2$ tournament selection is used. Since the breeding of two parents results in a single child, $2N_c$ tournaments are played to breed N_c children.

9. SINGLE-MODE MICROSTRUCTURED OPTICAL FIBRE DESIGN

Conventional single-mode optical fibres have been manufactured in both silica and polymer. In silica, their main application is long-distance telecommunications, where the dispersion of only a single-mode contributes to overall bandwidth properties. The single-mode property is also important for sensing applications and gratings, for example, the single-moded property is required for sensing applications which rely on interferometry. The inclusion of a fibre Bragg grating within the polymer optical fibre (POF) core can be used for sensing, where physical bending or stretching of the fibre results in changes to the grating spectrum. Polymer is an advantage here for two reasons - the material itself is much less susceptible to breaking, and POF is more responsive than silica to changes in temperature and strain [5].

Microstructured versions of single-moded silica fibres have been manufactured [3]. They consist of hexagonal arrays of holes, and the designs themselves require multiple rings of holes to effectively confine modes to the core. The hexagonal arrangement is a result of the manufacturing method used, where a preform consists of glass rods stacked into a hexagonal array, then drawn to an optical fibre. The first polymer version of a microstructured single-mode fibre [11] consisted of a hexagonal array of holes, where a drilled preform design with 60 holes resulted in single-mode guidance over 1 m of poly-methyl-methacrylate (PMMA) fibre. Up till now, single-mode microstructured fibre designs have been based on hexagonal n_{symm}=6 arrangements of holes.

Single-mode MPOFs have also recently incorporated fibre Bragg gratings into the solid core, where a UV laser was used to imprint the grating [12]. It was observed that particular orientations of the laser with respect to the hexagonal cladding were more efficient than others at writing the grating. New arrangements of holes which still maintain single-moded guidance may help alleviate this problem. There are a number of other factors which contribute to the need for new single-mode microstructured designs. Different core sizes and holes arrangements may make coupling to fibres and sources more efficient. Designs with fewer holes may also be easier to manufacture. Although the results presented here focus on MPOF, the results and method are also applicable to silica MOF. The main difference lies in the ability to easily manufacture fibres which cannot be manufactured using stacking techniques.

9.1 Single-mode fibre design considerations

In previous examples [7,9] of microstructured fibre design which considered single-mode fibres, the confinement loss of modes was not explicitly evaluated. Rather, the single-mode condition was enforced by ensuring particular values of d,Λ, or by maintaining a ring of holes with larger radii to aid in light confinement. The problem with this approach is that single-moded operation was not always guaranteed, with different fibre designs exhibiting quite different loss properties. In the approach here, a fitness function is formulated which explicitly considers the confinement loss properties of modes.

9.2 Multi-objective fitness function

There are two confinement loss properties which fibres must have for single-moded operation. Firstly, the loss of the fundamental mode $l_{c,1}$ must be sufficiently low such that it is guided along the entire length of fibre L. Secondly, the confinement loss $l_{c,2}$ of the next mode relative to the fundamental mode must be sufficiently high so it is rapidly lost as it travels down the fibre, resulting in single-moded guidance. This is a fairly ambiguous definition since single-moded operation is length dependent. For example, $l_{c,1}$=0.1dB/m, $l_{c,2}$=1.0dB/m could be considered multi-moded for fibre length L=1m, but effectively single-moded for L=20m where the second mode would be undetectable. These two required conditions can be expressed numerically as two design objectives O_1, O_2:

$$O_1 = l_{c,1}$$

$$O_2 = - l_{c,2} + l_{c,1}$$

where both objectives are to be minimised. Although these two objectives could be combined into a single objective for optimisation, there are a number of reasons not to. Firstly, the ranges values of O_1,O_2 can differ by orders of magnitude, and the ranges are not known in advance. This makes the selection of appropriate weighting factors difficult. Secondly, expressing them as two objectives will help reveal information about their relationship since a group of designs will emerge, rather than a single design.

Given the multi-objective nature of problem, designs cannot be ordered as in a single objective problem. Thus, a Pareto dominance approach must be taken. To explicitly favour designs which have a better fundamental mode loss, a constrained dominance approach is taken. Designs are first compared according to $l_{c,1}$, using a loss threshold value of l_t=1dB/m, to determine feasibility. Design **a** dominates design **b** if

- If **a** and **b** are both feasible ($l_{c,1}(\mathbf{a}) \leq l_t$ and $l_{c,1}(\mathbf{b}) \leq l_t$), then **a** dominates **b** in the usual Pareto-optimal sense, otherwise,

- If **a** is feasible ($l_{c,1}(\mathbf{a}) \leq l_t$) and **b** is not ($l_{c,1}(\mathbf{a}) \leq l_t$), **a** dominates **b**, otherwise,

- If neither **a** or **b** is feasible, then $l_{c,1}(\mathbf{a}) > l_t$ and $l_{c,1}(\mathbf{b}) > l_t$, if ($l_{c,1}(\mathbf{a}) < l_{c,1}(\mathbf{b})$), then **a** dominates **b**.

The result is that designs which have a fundamental mode loss less than 1 dB/m dominate those which do not.

9.3 Running the GA

The number of generations the GA is run for is quite low. This is due to the computational effort required for fitness evaluations, where the evaluation of the confinement loss of the first 2 modes of a microstructure fibre is approximately 10 minutes. This results in a total of (N_p + 200 N_c) 10 / 60 = 1675 CPU hours, or 70 days of CPU time. Thus, considerable effort has been placed in the efficient parallelisation of the GA. Since the evaluation of objectives for each individual are running in parallel, the real time for 200 generations is 2 to 4 days, depending on the number of other users who are simultaneously using the computing cluster. The limitation on the number of generations due to the computational effort required has been discussed in other publications, for example, 15 to 25 generations in [9].

Since there is a limited timeframe, the mutation rates have been reduced so more emphasis is placed on making minor improvements to existing good genotypes rather than an emphasis on generating diversity [6]. The GA was initialised using a random starting population, where each individual had up to 6 holes. Unphysical designs (with $l_{c,1}$ much less than 0 dB/m), had their objectives values set to O_1,O_2=10^6, effectively removing them from the population since they would not be selected for survival. These fibres corresponded to 5 to 15% of designs produced per generation. This is a result of numerical inaccuracies when evaluating the confinement modes of complex microstructures [6]. Optimal designs were evaluated at much higher accuracies anyway, to confirm the optimal results.

The evolution from the initial population to the final non-dominated set is shown in Figure 7. The total objective space explored is shown as grey dots, where features indicate that some combinations of O_1,O_2 are more prevalent than others. In particular, a linear relationship between the two objectives is evident. This is due to a higher frequency of designs which have similar loss values for both modes. The GA evolved 17 non-dominated designs by Generation 200 (crosses in Figure 7). A representative group of designs with good single-moded properties (O_1 < 0.1 dB/m, O_2 < -10^{-3}dB/m) were hand selected from this set of 17 designs. These are shown in Figure 8.

9.4 Design themes

By focussing on the functional holes - the holes which are responsible for single-mode guidance, the selected designs from can be classified (Figure 8) into the following types:

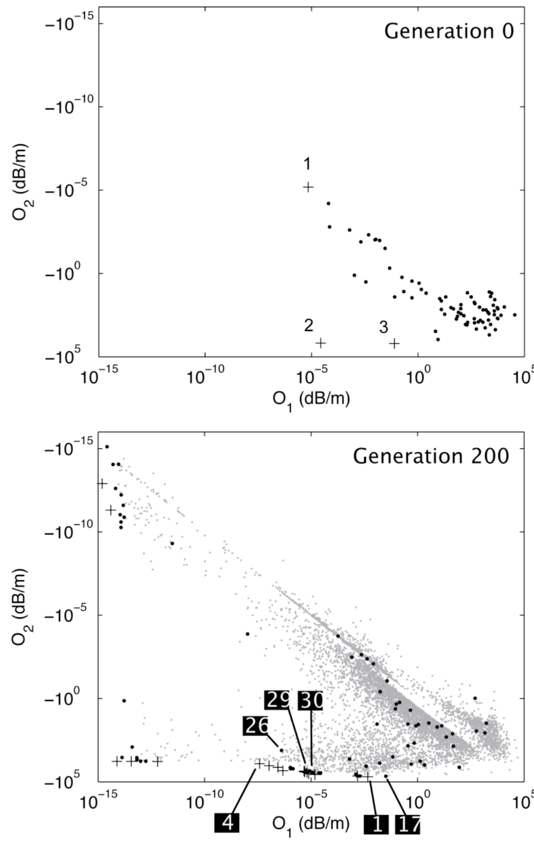


Figure 7. Population evolution from Generation 0 to 200. The grey dots indicate the objective values encountered during the search. The crosses indicate the final non-dominated set.

Type 1: A central ring of holes is interleaved evenly with a smaller ring of holes (Designs 30 and 4 (approximately)),

Type 2: A central ring of holes is interleaved unevenly with a smaller ring or multiple rings of holes (Designs 17, 1 and 29),

Type 3: A central ring of holes is surrounded by groups of holes further out (Design 26).

These points are particularly important since all previous single-moded microstructured fibres are like the hexagonal design, where holes are not interleaved, and are evenly spaced. The Type 1,2 and 3 microstructured designs employ different degrees of hole size variation, where typical microstructured designs use the same sized hole throughout the fibre profile. Fibre 17 uses quite similar sized holes, whereas the variation of holes size in the other designs is greater.

Single-moded guidance in hexagonal microstructured fibres mimics single-mode guidance in standard step-index fibres, where the hexagonal array of holes form a depressed cladding around the higher-index (non-microstructured) central region. Here, the discovered single-moded guidance mechanism is a result of an inner set of holes, which form a high air fraction ring. This inner set of holes confines the fundamental mode, but allows the second mode to leak out. The outer holes, which block the bridges between the inner holes, aid in reducing the confinement loss of the fundamental mode, but still facilitate leakage of the second mode. As an example, Design 17 is discussed. The outer holes can be rotated from the spiral type arrangement to more symmetrical

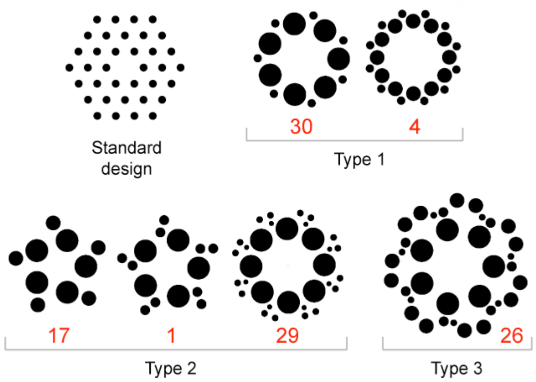


Figure 8. Three new types of single-moded microstructured optical fibres evolved by the GA.

positions relative to the inner set of holes. This does not have a significant effect on the confinement loss properties of fibre, and it remains effectively single-mode. However, significantly reducing the size of these outer holes, or discarding them completely, increases the confinement loss of the fundamental mode to >1dB/m, such that the fibre no longer effectively guides this mode.

10. DISCUSSION AND CONCLUSION

A general trend which is seen on the non-dominated set is that more complex designs result in a decrease of $l_{c,1}$. For example, ordering the evolved designs in Figure 8 from the smallest to largest $l_{c,1}=O_1$ corresponds to 4, 26, 29, 30, 1 and 17. Designs with lower $l_{c,1} \sim 10^{-10}$ are similar to Design 4, but with higher symmetries up to $n_{symm}=14$ and more interleaving holes.

The GA has discovered a number of single-mode designs with different symmetries. Most notable is the absence of $n_{symm}=6$ designs, which have been the primary type of single-mode microstructured fibre design used to date. The designs evolved all exhibit tightly confined fundamental modes and high loss second modes with $l_{c,2} > 10^4$ dB/m. In particular, the simpler designs such as 1 and 17 with 15 and 10 holes respectively have excellent single-mode performance. It is important to compare these to previous hexagonal structures, where the confinement of the fundamental mode and higher-order modes are strongly dependent on the number of holes. Studies have shown that 36 or more same sized holes are required to have $l_{c,1}<0.1$dB. Here, simpler designs, with fewer holes, but a variability in the size and positioning of those holes, has resulted in better loss characteristics, achieving single-mode guidance. Furthermore, the core sizes vary from design to design, ranging from 14μm (Fibre 17) to 23μm (Fibre 26), allowing easier coupling to sources and other fibres.

In summary, this work has successfully demonstrated the application of an embryogeny representation and GA to the real-world design of optical fibres, resulting in novel, simple single-moded microstructured optical fibre designs.

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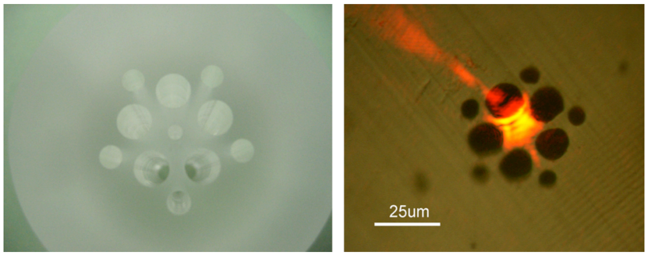

Figure 9. The drilled PMMA perform (left) corresponding to design 17, is drawn to an optical fibre (right), where red laser light is being guided down the core of the fibre.

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