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SIMULATION OF OPTICAL WAVELENGTH FILTER USING MULTIMODE INTERFERENCE (MMI) BASED ON SOL-GEL DERIVED ORGANIC-INORGANIC HYBRID MATERIALS

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Abstract. Simulation of optical wavelength filter for 1310nm and 1510nm operation on planar optical waveguides based on new VTT sol-gel derived material using Multimode Interference (MMI) technique is presented in this paper. Simulations of the material have demonstrated that in principle, similar filtering efficiency to other materials reported in MMI devices, in terms of extinction ratio (ER), it was simulated to be 18.4 and 21.6 dB for the wavelengths of 1310nm and 1550 nm, respectively. Meanwhile, the simulated insertion loss (IL) is around 1.43-1.64 dB for both filtering operations. The structure consists of two cascaded MMI sections, employing General Interference (GI) and Paired Interference (PI) mechanisms. The advantages of MMI based devices and sol-gel derived materials are discussed in this paper. The self-imaging principle, material characterizations and the final design of MMI based filter structure are also demonstrated in this paper.

Keywords: Optical waveguide; wavelength filter; MMI; general interference mechanism; paired interference mechanism; interference mechanisms; sol-gel derived materials

Abstrak. Simulasi penapis optik untuk 1310nm panjang gelombang dan 1510nm operasi pada pandu gelombang optik planar berdasarkan bahan-bahan baru VTT yang berasal sol-gel menggunakan teknik MMI disajikan dalam tulisan ini. Bahan simulasi telah menunjukkan bahawa, pada prinsipnya, mirip dengan kecekapan penapisan dari bahan lain yang dilaporkan dalam peranti MMI, dalam kes pemusnahan nisbah (ER), ia dicatatkan sebanyak 18.4dB dan 21.6dB untuk panjang gelombang 1310 nm dan 1550 nm, masing-masing. Sementara itu, kehilangan masukan (IL) adalah sekitar 1.43-1.64 dB untuk kedua operasi penapisan. Struktur ini terdiri daripada dua bahagian kaskad MMI, iaitu mekanisma gangguan umum (GI) dan mekanisma gangguan berpasangan (PI). Kelebihan peranti berasaskan MMI dan bahan-bahan yang berasal sol-gel dibahas dalam makalah ini. Prinsip pencorakan sendiri, ciri-ciri bahan yg digunakan dan struktur akhir penapis berasaskan MMI ini juga ada ditunjukkan dalam makalah ini.

Kata kunci. Gelombang pandu optik; penapis gelombang; MMI; mekanisma gangguan umum; mekanisma gangguan berpasangan; mekanisma gangguan; bahan-bahan terbitan sol-gel

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1.0 INTRODUCTION

Multimode Interference (MMI) devices are considerable interest as key optical components in photonics intergrated curcuits (PICs). The common principle of MMI device is based on destructive or constructive interferences occurring in the MMI device with a large number of multi-modes. It has been extensively studied as it offers numerous unique properties, such as low insertion/excess loss, large optical bandwidths, compactness, polarization insensitivity/ low polarization dependence, low crosstalk, and excellent fabrication tolerances. Consequently, it offers many potential applications such as splitters, combiners, couplers, mode converters, routers and filters [1]. In view of previous researches, various materials have been applied in the design and realization of MMI based wavelength filter. Amongst are those reported by Paiam *et al.* [2] on SiO_2OSiON rib waveguide system, Baojun Li *et al.* [3] on SiGe-Si material system, and Tsao *et al.* [4] on silicon-on-insulator (SOI). However, in this paper, as illustrated in Figure 1, the MMI device is presented for filtering the wavelength of 1.31μm and 1.55μm based on new multiprecursor organic-inorganic sol-gel derived material as prepared previously [5].

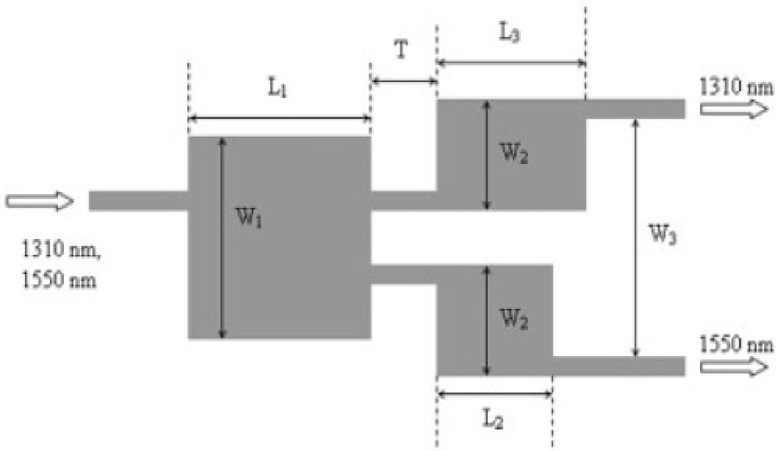

Figure 1 Optical wavelength filter layout [6]

Organic-inorganic sol-gel derived material is known to offer way out to the setback of its inorganic counterpart in the application of photonic devices, such as planar optical waveguides. Although they offer the same advantages through sol-gel processing technique that enable the production of materials with high homogeneity and purity in several forms, inorganic sol-gel derived materials however utilize high temperature processing, indirect patterning, and having a low thermo-optic coefficient [7]. On the other hand, organic sol-gel derived materials are introduced within the organic-inorganic materials which can function as organic modifiers or organic networks. These lead to the fabrication of more flexible products and also decrease the problem of shrinkage significantly [8, 9]. To reveal the properties and characteristics of the material, many studies have been done on organic-inorganic sol-gel derived materials especially with the presence of precursor such as titania or any other refractive index modifiers [10-11]. Subsequently, the existence of C=C double bond in the organic components, plus by the aid of photoinitiator and catalyst, organic-inorganic sol-gel derived materials turn out to be photopatternable. Therefore, optical waveguide micropatterning by means of photolithography technique is possible with the photopatternable organic-inorganic sol-gel derived materials [12-13].

2.0 MATERIALS AND METHODS

In this study, material applied for MMI wavelength filter structure design is based on sol-gel derived material as prepared previously [5]. As illustrated in Figure 2, the inorganic precursor tetraethoxysilane (TEOS), photopatternable organic component with shorter organic chain vinyltriethoxysilane (VTES), and refractive index modifier tetrabutoxytitanate (TTBu), were used to synthesis the hybrid organic-inorganic VTES/TEOS/TTBu (VTT) sol. For the sake of suitability of the proposed derived hybrid material (VTT), analysis of characterization on the physical properties such as thickness, surface roughness and uniformity were carried out and reported.

Prism coupling measurement made resulted in a value of refractive index and thickness of the planar optical waveguide as 1.4887 and 3.65 µm, respectively. These values are agreeable as compared to the cut-off thickness calculation and also to the SEM images [5]. It also shows that a single mode channel optical waveguide is realizable provided that the thickness lies within the range of 0.84 µm to 2.99 µm. Thus, for this particular MMI based filter design, the width of input waveguide is set to be 2.8μm which lead to the single mode waveguiding ability. For the substrate and cladding, Quartz/SOS and SiO_2 were used where their refractive indices are known as 1.4442 and 1.45 respectively.

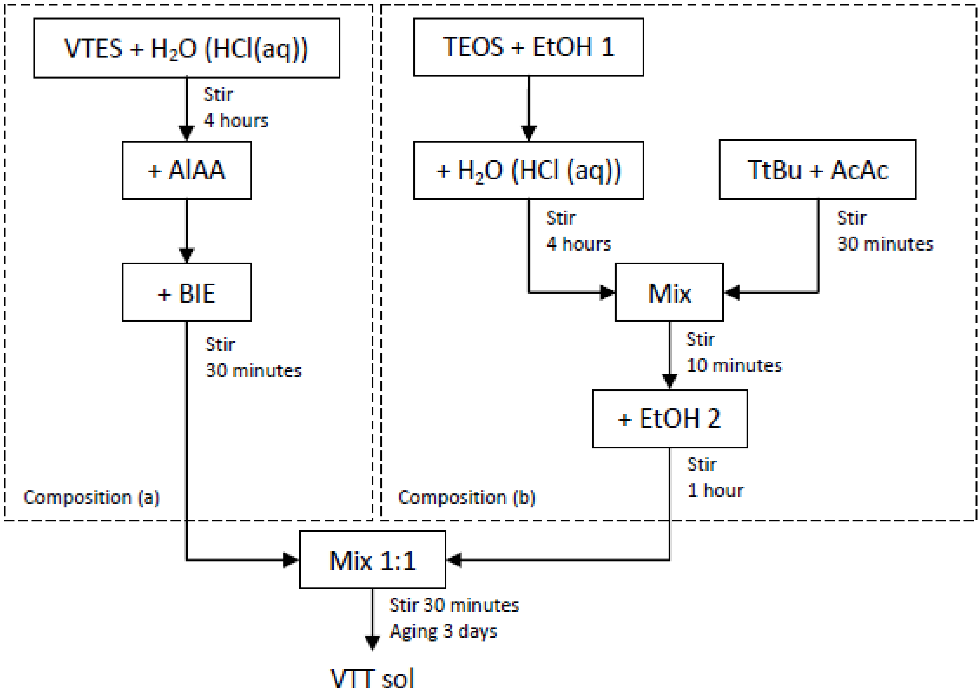

Figure 2 Preparation flow chart of VTT sol by sol-gel process [5]

Basically, the operation principle of the MMI device is based on self-imaging effect, a property of multimode waveguides by which an input field is reproduced in single or multiple images at periodic intervals along the propagation direction of the guide [14]. Light intensities in the MMI waveguide exhibit various distributions as they propagate at the positions relative to the beat length, L_μ defined by [14]:

$$L_\mu = \frac{\mu}{\beta_0 - \beta_1} \approx \frac{4nW_e^2}{3\lambda_0} \qquad (1)$$

where β_0 and β_1 are propagation constants of the fundamental and the first order lateral modes respectively, λ_0 is a free space wavelength, n is an effective index and W_e is an effective width of the multimode waveguide. The lateral modes in the MMI section have different propagation constants. At certain distances, a beating phenomenon occur where constructive interference between the modes will produces single or multiple self images of the input field. Considering all modes are excited in the MMI section, the resonant images due to constructive interference will occur at [14]:

$$z = p(3L_{\mu}) \tag{2}$$

Depending on even or odd value of *p*, direct or mirrored images of the input field is formed at particular *z* position. Because of no restrictions on modes excitation, this self-imaging mechanism is called GI scheme. In case where the modes 2, 5, 8,... in the MMI section are not excited, the resonant images occur at [14]:

$$z = p(L_{\mu}) \tag{3}$$

This phenomenon is called the paired interference (PI) scheme and allows the design to be three times shorter. This type of MMI scheme can be realized by placing the input access waveguides at 1/3 or 2/3 of MMI section width [15]. The essence of two-port filtering is to separate the incoming optical wavelengths such that λ_1 is filtered in one output and λ_2 is in the other output. An MMI waveguide can separate these wavelengths if it is in bar-coupled state for one wavelength and cross coupled state for another wavelength. For shorter device length, PI scheme is considered and this can be written as:

$$L_d = pL_{\mu\lambda_1} = (p+q)L_{\mu\lambda_2} \tag{4}$$

where *p* is a positive integer, *q* is an odd integer and $L_{\mu\lambda_i}$ is a beat length for wavelength λ_i. Noted that L_{μ} is inversely proportional to the wavelengths. To minimize device length, *p* and *q* should be as small as possible. Therefore, *p* and *q* can be determined once (4) is known. The beat length ratio of $(1+\frac{q}{p})$ is determined by simulating the ratio of $\frac{L_{\mu\lambda_1}}{L_{\mu\lambda_2}}$, taking λ_1 as 1310nm and λ_2 as 1550nm, as a function of MMI width.

3.0 RESULTS AND DISCUSSION

The beat length ratios, $\frac{L_{\mu 2}}{L_{\mu 1}}$ obtained from 2D Mode Solver are tabulated as shown in Table 1 and the corresponding graph in which relates between the parameter of beat length ratio and MMI width is shown in Figure 3. The modes were simulated by varying the width of MMI section from 20μm to 40μm for both wavelengths of 1310nm and 1550nm.

Table 1 Beat length ratio for different MMI section width

W	N_0(1.55)	N_1(1.55)	N_0(1.31)	N_1(1.31)	$L_{\pi 1}$(1.55)	$L_{\pi 2}$(1.31)	$L_{\pi 2}/L_{\pi 1}$
20	1.4883	1.4869	1.4884	1.4874	587.5307	680.8449	1.1588
21	1.4883	1.4871	1.4884	1.4875	643.6236	746.5664	1.1599
22	1.4883	1.4872	1.4884	1.4876	702.2854	815.3155	1.1609
23	1.4884	1.4873	1.4885	1.4877	763.5017	887.1132	1.1619
24	1.4884	1.4875	1.4885	1.4878	827.2844	961.9339	1.1628
25	1.4884	1.4875	1.4885	1.4879	893.6396	1039.7816	1.1635
26	1.4884	1.4876	1.4885	1.4879	962.5536	1120.6734	1.1643
27	1.4885	1.4877	1.4885	1.4880	1034.0227	1204.5755	1.1649
28	1.4885	1.4878	1.4885	1.4880	1108.0610	1291.5311	1.1656
29	1.4885	1.4878	1.4885	1.4881	1184.6530	1381.5068	1.1662
30	1.4885	1.4879	1.4886	1.4881	1263.8205	1474.5278	1.1667
31	1.4885	1.4879	1.4886	1.4881	1345.5328	1570.5174	1.1672
32	1.4885	1.4880	1.4886	1.4882	1429.8365	1669.6406	1.1677
33	1.4885	1.4880	1.4886	1.4882	1516.6934	1771.7068	1.1681
34	1.4885	1.4881	1.4886	1.4882	1606.1178	1876.8984	1.1686
35	1.4885	1.4881	1.4886	1.4883	1698.0719	1985.0289	1.1690
36	1.4886	1.4881	1.4886	1.4883	1792.6121	2096.2012	1.1694
37	1.4886	1.4882	1.4886	1.4883	1889.6908	2210.4482	1.1697
38	1.4886	1.4882	1.4886	1.4883	1989.3729	2327.6475	1.1700
39	1.4886	1.4882	1.4886	1.4883	2091.5985	2448.0490	1.1704
40	1.4886	1.4882	1.4886	1.4884	2196.4007	2571.3501	1.1707

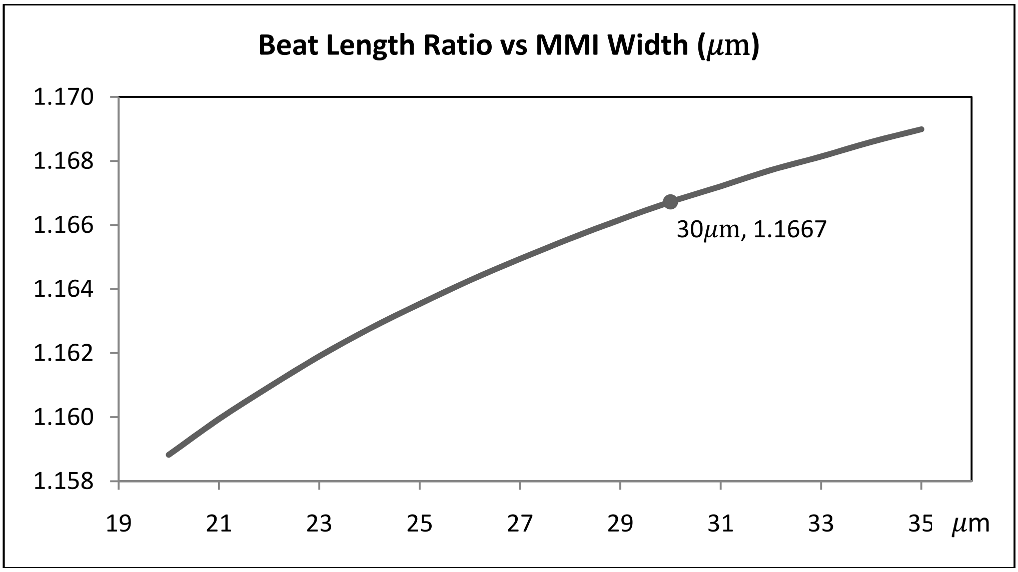

Figure 3 The graph of Beat Length Ratio vs MMI Width (μm)

From the graph, it was shown that for MMI section width, W_1=30μm, an approximate beat length ratio of 1.1667 is obtained. This ratio provides useful ideas on the value of respective p and q parameter which can be further written as;

$$L_d = 6L_{\mu,1310} = 7L_{\mu,1550} \tag{5}$$

From (5), it implies that the first stage of MMI filter acts as cross coupler for 1550 nm wavelength and bar coupler for 1310 nm wavelength. With the MMI width used (W_1=30μm), the output access waveguide spacing is only 10μm. To increase the spacing one could interpose S-curve waveguides. However, in our design we use an MMI cross coupler operating in each output waveguide to offset the outputs by about 17μm, thereby increasing the separation to W_3=44μm.

These MMI couplers operate in the GI mode and have a width of W_2=15μm. The schematic layout of the complete filter is shown in Figure 1. The values of L_1, L_2, L_3, and T for this particular MMI structure are 8847μm, 1193μm, 1037μm and 200μm respectively. 2-dimensional beam propagation method (2D-BPM) from Optiwave is employed to model a TE light propagation through the MMI filter. The results of this simulation for 1.31μm and 1.55μm wavelengths are shown in Figure 4(a) and (b) respectively. It was observed that the two lights at different wavelengths emerge from the different output ports, which verify the proposed wavelength filtering device.

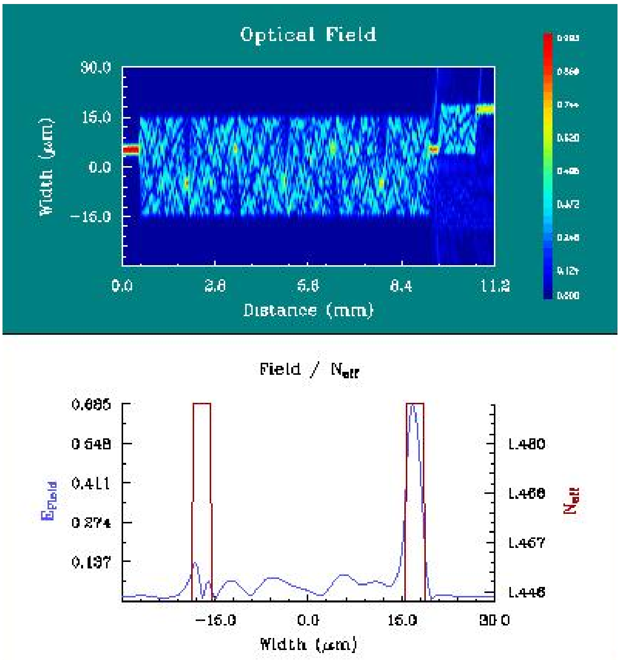

Figure 4(a) 2D-BPM simulation intensity at bar output for 1310 nm

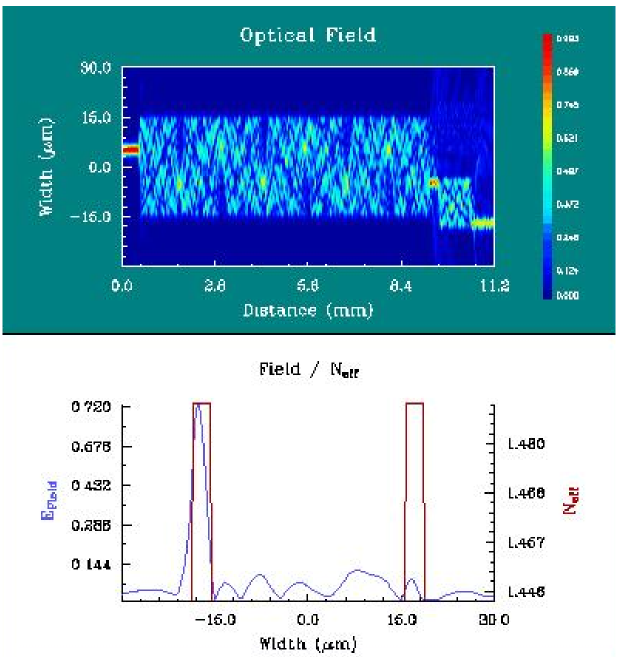

Figure 4(b) 2D-BPM simulation intensity at cross output for 1550 nm

To characterize its performance, two parameters such as Extinction Ratio (ER) and Insertion Loss (IL) are employed which are defined as follows [16]:

$$ER = 10\log\frac{P_r}{P_w}$$

$$IL = -10\log\frac{p_r}{P_i}$$

where P_r and P_w denote the light intensities in the right and wrong output port of the filter while P_i denotes the light intensity at the input port. The extinction ratio was simulated to be 18.4dB and 21.6dB for 1310nm and 1550nm, respectively. Meanwhile, the simulated insertion loss is around 1.43-1.64 dB for both filtering operations. The simulated results have shown that the new sol-gel based MMI filter has similar filtering efficiency to other materials reported [2-4, 6].

4.0 CONCLUSION

A new structure design of MMI wavelength filter for the 1310nm and 1550nm operation on planar optical waveguides based on VTT sol-gel derived material has been successfully demonstrated. The structure consists of two cascaded MMI sections, employing General Interference (GI) and Paired Interference (PI) mechanisms. The new sol-gel based MMI filter is proven to function well with simulated crosstalk of -18.4 and 21.6 dB for 1310nm and 1550nm, respectively. The succeeded development of sol-gel derived materials in previous work with numerous unique and excellent properties has led to the new realization of sol-gel based MMI filter as successfully presented and discussed in this paper.

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