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ARRAYED-WAVEGUIDE GRATING FOR WAVELENGTH DIVISION MULTI/DEMULTIPLEXER WITH NANOMETRE RESOLUTION

Indexing terms: Optical communications, Optical waveguides, Optical waveguide components, Optical multi/demultiplexers

A novel diffraction grating based on arrayed channel waveguides has been proposed for nanometre-spaced wavelength division multiplexing. A grating with a diffraction order of 20 has been fabricated using a composite glass waveguide. A wavelength resolution of 0·63 nm has been achieved in the 1·3 μm wavelength band.

Introduction: Recent advances in DFB laser technologies, for example the realisation of a laser array of 20 wavelengths with a wavelength spacing of 1 nm,[1] encourage us to construct dense wavelength division multiplexing optical communication systems. One of the problems to be solved is how to multiplex and demultiplex these densely packed optical signals. A promising approach to cope with this problem is to introduce an arrayed-waveguide grating as a dispersive medium suitable for integration with DFB-lasers. Smit[2] reported the fabrication of an array of concentric bent waveguides as a demultiplexer operating in the 0·63 μm wavelength band. The wavelength resolution of this arrayed-waveguide grating was, however, limited to several nanometres, because of the limited path difference in the geometry of the concentric bent waveguides. This letter describes a successful extension of the array-waveguide grating to a wavelength resolution of 1 nm or less in the 1·3 μm wavelength band.

Fundamentals and design: The layout of the arrayed-waveguide grating proposed in this letter is shown in Fig. 1. The grating consists of single-mode channel waveguides of different lengths with bent parts of the same curvature radius. This layout makes it possible to select any value of the waveguide length difference required for higher resolution.

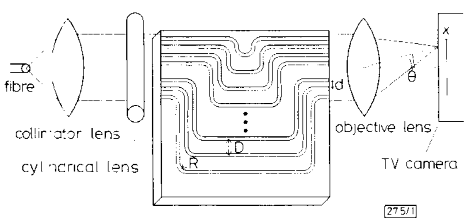

Fig. 1 *Proposed arrayed-waveguide grating and experimental set-up*

Length difference between adjacent channel waveguides is given by $\Delta L = 2(D - d)$

Any two adjacent waveguides have the same length difference ΔL which results in the phase difference $2\pi n_c \Delta L/\lambda$, where n_c is the effective refractive index of the channel waveguide and λ is the light wavelength. The light emitted from the channel waveguide exits is diffracted at an angle θ which satisfies

$$n_c \Delta L + n_s d \sin\theta = m\lambda \tag{1}$$

where n_s is the refractive index of converging space, d is the pitch of the channel waveguides at their exits, and m is the diffraction order.

The dispersion $dx/d\lambda$, where x is the position of the converged beam on the focal plane (see Fig. 1), is derived by differentiating eqn. 1 as

$$\frac{dx}{d\lambda} = \frac{fm}{n_s d} \tag{2}$$

where f is the focal length of the converging lens. The full width at half-maximum (FWHM) of the converged beam is at best $(\lambda f)/(n_s N d)$ because of the diffraction limit, where N is the number of channel waveguides. Using the FWHM and the dispersion, the wavelength resolution $\Delta\lambda$ is given by

$$\Delta\lambda = \frac{\lambda}{Nm} \tag{3}$$

as for a conventional diffraction grating. Eqn. 3 shows that high-order diffraction is needed for high resolution. In eqn. 1 the diffraction order is given by $m = n_c \Delta L/\lambda$ for small θ. Therefore an arrayed-waveguide grating with large ΔL can multiplex and demultiplex light waves with a small wavelength spacing. In Fig. 1 we can design ΔL as large as is needed for the desired wavelength resolution.

Experiments: SiO_2/C7059/SiO_2 composite glass waveguide,[3] which had a refractive index difference of 5%, was used so that a small radius and a narrow pitch were realised. A 4 μm-thick SiO_2 base layer was made by oxidising an Si substrate in wet O_2. A 1·2 μm-thick Corning 7059 glass core was deposited using RF magnetron sputtering, and channel waveguides were formed using reactive ion beam etching after the photolithographic process. Then a 4 μm-thick upper SiO_2 cladding layer was deposited by the sputtering method. The sectional dimension of the channel waveguides was 1·2 μm × 1·5 μm. The length difference ΔL was designed as 17·54 μm corresponding to $m = 20$, and the number of channel waveguides, N was 150, to obtain a wavelength resolution of less than 1 nm. A bent part radius of 1 mm and a pitch $d = 8$ μm were selected. The sample thus fabricated was about 1 cm square.

Light from a tunable external-cavity semiconductor laser operating at a wavelength of 1·3 μm was collimated and coupled into 150 channel waveguides through a cylindrical lens. The diffracted light from the channel waveguides was focused onto the imaging plane of a TV camera by an objective lens ($f = 36·6$ mm). Fig. 2 shows the experimental focal position shift of diffracted light when the wavelength was changed from 1·280 to 1·310 μm in steps of about 2 nm. From the relation between the position and the wavelength, the dispersion is estimated as 95·7 μm/nm. This value is in agreement with the value of 91·5 μm/nm calculated using eqn. 2. The discrepancy between the measured and calculated values results from the material and structural dispersion of the channel waveguide itself.

No significant polarisation sensitivity was observed in the present arrayed-waveguide grating. This is in sharp contrast to a conventional Bragg grating fabricated in a slab waveguide. A possible reason is that the channel waveguide structure adopted in this work exhibits smaller birefringence than that of the slab waveguide.

The measured FWHM was 60 μm, which was near to the diffraction limit of 40 μm. This suggested that there was no serious wavefront distortion due to either birefringence or

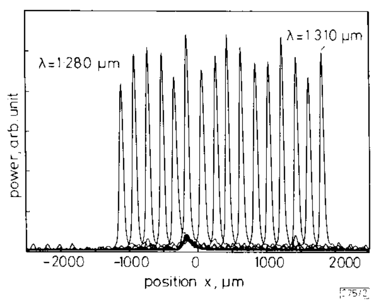

Fig. 2 *Experimental wavelength dependence of focal position*

variation of effective refractive index in the channel waveguides. From the dispersion and the FWHM, the wavelength resolution is experimentally estimated as 0·63 nm. This value is near to the value of 0·43 nm calculated using eqn. 3.

One of the remaining problems to be solved is the replacement of the bulk-type input/output lenses in Fig. 1 with waveguide-type elements. The integration of such elements is now in progress.

Conclusion: A new type of arrayed-waveguide grating has been proposed. This grating consists of channel waveguides of different lengths with bent parts of the same curvature radius. The grating was fabricated with composite glass waveguide using the conventional photolithographic technique. The wavelength resolution obtained was 0·63 nm at a diffraction order of 20. This type of arrayed-waveguide grating is expected to meet WDM demands for densely packed tens of channels with a wavelength spacing of 1 nm or less.

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GENERALISED TYPE-II HYBRID ARQ

Indexing terms: Telecommunications, Information theory, Codes and coding, Hybrid ARQ communications, Block codes

The letter gives general descriptions of II-GHARQ and defines a concept of minimum distance distributed sequence (DDS) which is more exact to represent the error-correcting capability of the codes used in II-GHARQ. Some DC codes which have a better DDS than KM codes are designed and Hadamard transform decoding is regarded as a common decoding method. Both analysis and simulation results indicate that II-HARQ using DC code gives a good throughput efficiency.

Introduction: When a very low error rate is needed in communications, ARQ schemes are often adopted. One of the main parameters of ARQ systems is throughput efficiency. Type-II hybrid ARQ schemes (II-HARQ)[1] were proposed to improve the throughput when channels became worse. To improve the throughput further, Krishna *et al.*[2,3] proposed generalised type-II hybrid ARQ (II-GHARQ). This letter gives a general description of II-GHARQ and defines a concept of minimum distance distributed sequence (DDS) to show the error-correcting capability of the codes in II-GHARQ exactly. Some codes, called DC codes, which possess good DDS, are researched and maximum-likelihood decoding can be realised by Hadamard transform[4] uniformly. Analysis and simulation results indicate that II-GHARQ has no improvement on the throughput compared to II-HARQ used with DC codes.

General description of codes: In ARQ systems K information bits from a source are encoded as an (N, K) detecting code C_f and then the N bits are transmitted to the receiver. If there are errors in the received N bits, retransmission of the N bits or its transformations is carried out until no errors are detected. Assume that the N-bit code C_f to be transmitted is $A = [a_1, a_2, \ldots, a_j, \ldots, a_L]$ and the ith transmission of A over the channel is a transformation $B^{(i)}$ of A, where

$$B^{(i)} = [b_1^{(i)}, b_2^{(i)}, \ldots, b_j^{(i)}, \ldots, b_L^{(i)}] \qquad i = 1, 2, \ldots \quad (1)$$

in which a_j and $b_j^{(i)}$ consist of n bits, respectively, and $nL = N$. In II-GHARQ the $B^{(i)}$ is required to be an invertible transformation of A, i.e. an $n \times n$ invertible matrix M_j exists which satisfies $b_j^{(i)} = a_j M_j$. We define the code C as

$$C = [b_j^{(1)}, b_j^{(2)}, b_j^{(3)}, \ldots] = a_j[M_1, M_2, M_3, \ldots] \quad (2)$$

The code C is defined completely by the following generator matrix:

$$G = [M_1, M_2, M_3, \ldots] \quad (3)$$

The code depth is defined as the smallest positive integer m for which $M_j = M_{j+m}$, for example $m = 1$ and $m = 2$ for pure ARQ and II-HARQ, respectively. Generally speaking, $G_i = [M_1, M_2, \ldots, M_i]$ generates an (in, n, d_i) linear block code, where d_i is the minimum Hamming distance. We call $\{d_1, d_2, \ldots\}$ the minimum distance distributed sequence (DDS). The error-correcting capability of the code C is represented exactly by the DDS.

Some good codes and comparisons of DDS: To realise II-GHARQ, Krishna and Morgera[2] gave a kind of code, called KM codes, with $m = 3$ and 4. The DDSs of KM codes are almost the same as those of the following codes with $m = 2$ designed by us. Let $V = (v_1, v_2, \ldots, v_n)$ and $DV = (v_n, v_1, \ldots, v_{n-1})$ in which D is a cyclic shift operator. Assume that

$$G = [G_1, G_2, G_1, G_2, \ldots] \quad (4)$$

i.e. $G_i = G_{i+2}$, where $G_{2i-1} = I$ ($i = 1, 2, \ldots$; I is a unit matrix), and

$$G_{2i} = \begin{bmatrix} V \\ DV \\ \vdots \\ D^{n-1}V \end{bmatrix} \quad (5)$$

We call the codes defined by eqn. 4 $(2n, n)$ double cyclic codes or DC codes. The V with $m = 4$ to 8 are given in Table 1.

Table 1

n	4	5	6	7	8
V	0111	00111	011111	0011111	01001111

II-GHARQ using DC codes is also a II-HARQ scheme. Table 2 gives comparisons of DDSs among DC and KM codes.

Table 2

Code	d_2	d_3	d_4	Code	d_2	d_3	d_4
(12, 4)KM	3	5	7	(18, 6)KM	3	6	8
(8, 4)DC	4	5	8	(24, 6)KM	3	6	9
(15, 5)KM	3	5	7	(28, 7)KM	3	6	10
(10, 5)DC	4	5	8	(14, 7)DC	4	5	8
(15, 5)MDC	4	7	8	(32, 8)KM	3	6	9
(12, 6)DC	3	6	8	(16, 8)DC	5	7	10

Note that the (15, 5)MDC code with depth $m = 3$ has the generator matrix $G = [G_1, G_2, G_3, \ldots]$, where G_1 and G_2 are the same as those of the (10, 5) DC code and $G_3 = [V^T, (D^2V)^T, (D^4V)^T, (DV)^T, (D^3V)^T]^T$. When $n = 5$ the DDS of the (15, 5) MDC code is the best.

From Table 2 we can see that the differences between KM and DC codes are very small and may conclude that the