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Large-scale fibre-array multiplexing

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***Abstract*. The possibility of creating a fibre multiplexer/demultiplexer with large-scale multiplexing without any basic restrictions on the number of channels and the spectral spacing between them is shown. The operating capacity of a fibre multiplexer based on a four-fibre array ensuring a spectral spacing of 0.7 pm (~ 10 GHz) between channels is demonstrated.**

Keywords: *multiplexer/demultiplexer, spectral multiplexing, dispersive system, resolution, fibre-optic communication*

Attempts to modify spectral multiplexing/demultiplexing systems of fibre-optic communication channels aimed at increasing the number of channels led to the development of multiplexers/demultiplexers (M/D) with extremely narrow spectral channels. Apart from the spectral waveguide M/D (WDM/D systems) with $N = 8$ and 16 channels with a spectral spacing ~ 200 GHz, multiplexers with $N = 32 - 40$ and spectral spacing ~ 100 GHz (DWDM systems with large-scale multiplexing) as well as with $N = 64 - 128$ and channel spacing 50 GHz and below (HDWDM systems with large-scale multiplexing) were designed and tested. In recent publications devoted to this problem, the creation of 320- and 480-channel multiplexers with a spectral spacing 10 GHz has been reported [1, 2]. The main principle restriction on the number of channels in planar multiplexers is a limited size of crystals used in multiplexers.

In this work, we present the schematic of a two-cascade fibre-array M/D with $N = 10^4$ channels (Fig. 1). The input signal *1* containing radiation at wavelengths $\lambda_1, ..., \lambda_N$, is coupled into the input of cascade I of the multiplexer consisting of a fibre array *2*, focusing devices *3* at the input and output of the fibre array, and the output optical fibres *4*. Radiation from the output of cascade I is directed at the inputs of the cascade II of the multiplexer consisting of M identical multiplexers forming devices analogous to the cascade I multiplexer but with a higher resolution. The fibre array of cascade I consists of $M_{\rm I}$ segments of optical fibres with a constant difference $h_{\rm I}$ between the lengths of adjacent fibres, and constitutes the dispersive system of this multiplexer.

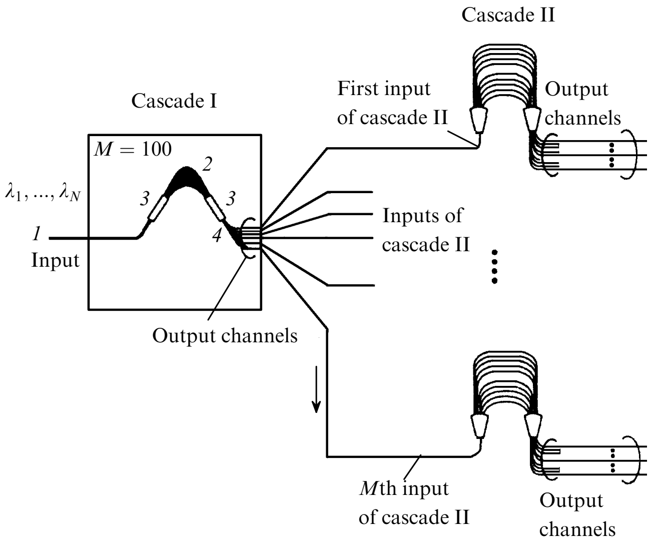

Figure 1. Schematic of a two-cascade fibre M/D.

Fibre arrays of cascade II, which serve as the dispersive systems of its multiplexers, have $M_{\rm II}$ elements and ensure a higher resolution due to an increase in $h_{\rm II}$.

By specifying the spectral dispersion range $\Delta\lambda$, the number N of channels, and parameters of the focusing system, we can calculate the main characteristics of the multiplexer such as the constant difference h between the lengths of adjacent elements of the fibre array, which determines the number M of array elements and the minimum resolvable spectral interval $\delta\lambda$, the angular dispersion D_φ and the linear dispersion $D_{\rm L}$, the minimum separation δx between output channels, and the resolving power $\Re$ [3, 4]. The radiation from each output of cascade I has a spectral range $\delta\lambda_{\rm I}$, while the dispersion range $\Delta\lambda_{\rm II}$ of each multiplexer of cascade II must cover the spectral range $\delta\lambda_{\rm I}$. This means that the condition $\Delta\lambda_{\rm II} = \delta\lambda_{\rm I}$ determining the difference $h_{\rm II}$ in the lengths of adjacent array elements of cascade II is satisfied. It should be noted that the lengths of the shortest and longest array elements of cascade I are $h_{\rm I}$ and $M_{\rm I}h_{\rm I}$, while those for the array elements of cascade II are $h_{\rm II}$ and $M_{\rm II}h_{\rm II}$, respectively.

The parameters of a fibre M/D with $N = 10^4$ channels were calculated for the spectral range 1530 – 1560 nm. Thus, in this range, the dispersion region $\Delta\lambda$ of the fibre array in cascade I was assumed to be equal to 26.4 nm (3300 GHz). If we use the cascade I array with $M = 100$ elements, the realisation of a 10^4-channel multiplexer requires the pres-

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ence in cascade II of 100 elements with a 0.26-nm spread in wavelengths. By calculating the multiplexer parameters, we assumed that the diameters of the fibre core and cladding are 10 and 100 μm respectively, while the focal length f of the lens and its diameter D are 2 and 1 cm, respectively. Table 1 contains the values of the fibre M/D parameters calculated for cascades I and II.

by depositing an α-Si film. In the former case, a dynamic tuning of the phase of each channel was realised, which provided the phase error less than 10° and the cross-talk below −35 dB. In the latter case, the static tuning reduced the root-mean-square deviation of the phase to 2° and the cross-talk to below −30 dB for all the 16 channels of the multiplexer.

Table 1.

Cascade	N	$\Delta\lambda$/nm	h/μm	$\delta\lambda$/nm	$D_{\varphi}/\mu m^{-1}$	D_L	δx/μm	$\Re$
I	100	26.4 (3300 GHz)	60	0.264 (33 GHz)	4	8×10^4	21	6×10^3
II	100	0.264 (33 GHz)	6000	0.264×10^{-2} (0.33 GHz)	400	8×10^6	21	6×10^5

Based on the geometrical characteristics obtained, cascade I of the multiplexer can be prepared on a single substrate, e.g., on SiO_2/Si or InP. The fabrication of such a multiplexer with 128 channels was reported in [5]. The fabrication of such a planar two-cascade multiplexer on a single substrate is problematic, because the size of the longest element in a cascade II multplexer exceeds 60 cm. Apparently, it is expedient to consider a hybrid scheme in which cascade I is constructed as a planar waveguide, while cascade II is formed by optical fibres. Because of very small energy losses in optical fibres, the considerable length of array elements does not lead to a deterioration of the multiplexer characteristics.

As the focusing elements, one can use either focusing waveguide plates [6] or the hybrid version of volume lenses. The single-mode fibres can be coupled into the input/output with the help of gradient lenses or special fibres with expanding outputs. In addition, the technologies used in Ref. [7] for creating fibre splitter modules can also be applied.

The main energy losses occur upon signal coupling into the waveguide array at the fibre-waveguide and fibre-fibre couplings. These losses are estimated as 1 – 5 dB. For the sake of convenience and in order to reduce losses, it is expedient to couple the signal into the fibre array bundle of densely packed fibres with a circular cross section in the case of a lens focusing system. For this purpose, we can also use a monolithic spherical glass surface, on which the contacting input fibres form a converging wavefront. The array fibres are brought in contact at the focus from the other side. Note that we can also use [3, 8] the reflection version of a demultiplexer having double the resolution of a transmission demultiplexer of the same size.

The main difficulty in the realisation of a fibre M/D is associated with the need to maintain the length of fibres in the fibre array to within 0.01 λ [9]. Such an accuracy can be achieved by modifying the already prepared fibre array by its heating, bending, etc. [10 – 12]. Calculations based on the technique described in [10, 11] show that a bent region of the fibre with the above-mentioned parameters (length 1 – 5 cm and radius of curvature $R = 5$ cm) provides the variation in the optical path length from 0.01 to 0.09 μm.

In order to compensate for the phase errors, a waveguide array consisting of small segments of waveguides was inserted at the centre of the waveguide M/D. The phase shift was provided by two methods: due to the thermooptical effect as a result of the waveguide temperature variation produced by thin-film heaters, or due to the piezooptical effect produced

The version of phase tuning of the multiplexer channels with the help of an auxiliary waveguide array described in [13], which was realised in a 1.44 mm long InGaAsP structure with channel waveguide spacing 85 μm, seems to be quite interesting. A phase shift of 0.4 rad/mA was produced by an injection current which changed the refractive index of the structure by changing the density of charge carriers. Thus, the desired accuracy for fibre M/D can be ensured by using one of the above correction techniques.

The efficiency of the fibre multiplexer proposed in this work was demonstrated with the help of a prototype with an array consisting of four fibres, the difference in the lengths of adjacent fibres being $h = 9$ cm [11]. The prototype ensured the spectral resolution $\delta\lambda = 0.7$ pm ($\sim$ 10 GHz) and the resolving power $\Re = 10^6$. By way of an illustration, the prototype was used to resolve two longitudinal modes of a He – Ne laser separated by 0.8 pm (Fig. 2).

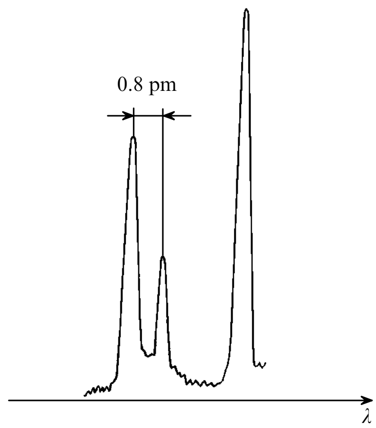

Figure 2. Spectrum of the longitudinal modes of a He – Ne laser resolved with the help of an experimental prototype

There are no basic limitations on the number of channels or the separation between them in the proposed fibre M/D. The spectral spacing between the channels of fibre M/D can be increased (i.e., the value of $\delta\lambda$ can be decreased) according to the scheme described above and used in optical communications. The minimum bandwidth of the narrow channels will be determined only by the temperature stability of the multiplexers and the stability of the frequency of the radiation sources.

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