nonradiative recombinations in the slightly larger growth interface between the MQW layers and the InP buffer layer. The quantum efficiency should be improved by the use of the optimum number of quantum wells and grating depth.

Laser spectra were observed at injection currents below and above threshold (20–60 mA). More than 90% of the 115 devices with 125 and 250 μm cavity lengths exhibited single longitudinal mode oscillation without the use of a facet coating or $\lambda/4$ phase shift in the grating. A sidemode suppression ratio as high as 52 dB was obtained for the laser with 125 μm cavity length under DC operation. The high single-mode oscillation yield can be attributed to the gain-coupling effect of the periodic MQW active grating, even though there is also index coupling. Shown in Fig. 3 are spectra for different laser cavity lengths. The spectra exhibits asymmetric distributions with the longer wavelength side having higher intensities. This result is consistent with theoretical prediction [6]

Fig. 3 Laser spectra at $I = 60$ mA showing single longitudinal mode operation

52 dB sidemode suppression ratio is obtained for $L = 125$ μm

because the present structure has an active grating whose gain periodicity is in phase with that of the index, longer wavelength lights are favourable in optical gains. The coupling strength (κL) dependence of the laser spectra can be found by changing the cavity length. The spectrum for $L = 125$ μm shows a clear gain-coupling feature in which there is only one longitudinal mode and all the Fabry–Perot modes disappear. When L increases, the Fabry–Perot mode spacing becomes smaller and multimode oscillations take place. In this work, to enhance the gain coupling effect and show the feasibility of short cavity DFB lasers, deep gratings were etched in the quantum wells. Writing κL as $\kappa L = \kappa_{\text{index}} L + j\kappa_{\text{gain}} L$, we estimate from the width of the stop band ($\Delta\lambda = 6.8$ nm for $L = 250$ μm) the $\kappa_{\text{index}} L$ to be 7–8 which is almost three times greater than for conventional lasers. To achieve better laser performance, the optimum grating depth appears to be somewhat smaller than in the present work.

Conclusion: We succeeded in the fabrication of a novel index/gain-coupled DFB laser with a strained layer MQW active grating. The laser exhibited very clear spectral features due to gain-coupling effects. High singlemode yield (>90%) and low threshold current operations were obtained without the help of facet coatings or phase shifts in the grating.

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DESIGN OF TRELLIS WAVEFORM CODERS WITH NEAR-OPTIMUM STRUCTURE

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Indexing terms: Algorithms, Codes and coding, Information theory

In this Letter the combinatorial optimisation algorithm known as simulated annealing is used for the optimisation of the trellis structure of the next-state map of the decoder finite-state machine in trellis waveform coding. The generalised Lloyd algorithm which finds the optimum codebook is incorporated into simulated annealing so that near-optimum coding systems are designed. Comparison of simulation results with previous work in the literature shows that this method yields better coding systems than those published in the literature.

Introduction: Source coding, one of the main concerns of information theory, is the study of coding of information-bearing signals, so that they can be transmitted through finite transmission rate and noiseless communication channels to be recovered at the decoder with little or no distortion. When a waveform is encoded in a way to approximately recover the waveshape at the decoder, without any source modelling, the source coding technique is known as waveform coding. A high-performance source coding technique is known as trellis, lookahead, or delayed decision source or waveform coding [1]. Trellis waveform coding uses a finite-state machine as the decoder. This machine is defined by an output map, corresponding to the codebook, and a next-state map, corresponding to the trellis structure, both of which are functions of the channel symbol and the current state. The extension of the next-state map or the state transition diagram in time is known as a trellis structure, a weighted directed graph consisting of identical stages. Each stage corresponds to a time instant. The encoder is matched to the decoder, it examines the trellis and finds the channel sequence that leads to minimum distortion, which is the sum of the distortion values between the input and reproduction symbols. This can be accomplished by a trellis search algorithm. One such search

algorithm is the Viterbi algorithm (VA) [2]. The encoder in a trellis waveform coding system is simply a trellis search algorithm matched to the decoder finite-state machine. Therefore, the design problem reduces to the design of the decoder finite-state machine. This problem has been addressed by several authors in the literature [1, 3–5]. In this work, we optimise both the codewords and the finite-state machine structure, using a near-optimum approach.

Because the decoder is equivalent to the trellis structure, for a given set of codewords (quantisation levels), and a given input sequence, it is clear that finding the optimum decoder is equivalent to finding the trellis structure that will generate a channel sequence with minimum distortion at the decoder output. This is a combinatorial optimisation problem and can be solved by known optimisation methods. We propose the simulated annealing algorithm [6] for this purpose.

Simulated annealing: Simulated annealing (SA) is an optimisation algorithm which takes its motivation from metallurgy. There is a certain analogy between the annealing of solids and the problem of solving large scale combinatorial optimisation problems. The annealing of solids is a process in which a solid is heated up to a high temperature where virtually all dislocations are removed. The temperature is then decreased slightly, and kept at that value long enough so that the solid reaches equilibrium. The process is continued in this way until the temperature is very low, so that there are virtually no dislocations in the solid. At the end of the process, a minimum energy configuration in the solid is obtained. In simulated annealing, the problem is specified with the function to be optimised and the state space of the function parameters. The function to be optimised corresponds to the system energy in the annealing of the solids, and the state space to the configuration of dislocations on different energy levels. The algorithm is initiated by choosing an arbitrary initial state. The function is evaluated at this state. A neighbouring state is then chosen and the function value evaluated at this state is compared with the previous one. If the second value evaluated is 'better' than the first one, this state is chosen as the new state of the function. It is obvious that the function will evolve to be 'optimised' in this process, but it may get stuck in one of the local optima. Simulated annealing prevents this phenomenon by accepting some 'worse' neighbouring states as the new state of the function. This is performed according to the Metropolis criterion which generates an approximate Boltzmann distribution for the state probabilities when the equilibrium is reached [7]. For a detailed analysis and various applications of the simulated annealing algorithm, the reader is referred to References 8–10.

Simulated annealing applied to trellis waveform coding: In this Letter we propose using SA for the optimisation of the trellis structure. The state space is chosen to be all the possible state transitions in a single state of the trellis. We are interested in trellis waveform coders with rate 1 bit/sample. This imposes a constraint on the encoder structure: from each node, there are two outgoing branches which correspond to values of 0 and 1 for the binary channel code. We also constrain the number of input branches going into each node: there are two incoming branches. This constraint is imposed to obtain a more symmetric structure so that the search space is minimised and the possibility of pathological trellis structures is completely eliminated. The move set has been chosen to be just the flipping of two branches, so that the output of a move is again in the state space. The cost function is simply the minimum metric calculated by the VA. The initial value of the control parameter is calculated as suggested by Johnson *et al.* [11]. Geometric improvement is used as the cooling schedule. The lengths of Metropolis loops are determined experimentally. As the source, a first order Gauss-Markov source $\{X_n\}$ is used, defined by

$$X(n+1) = aX(n) + W(n) \quad n = 0, 1, 2, \dots$$

where $W(n)$ is a white zero-mean Gaussian time series. This source is chosen because it is a common model of real data and it is widely used in comparing data compression systems [1, 4, 5].

Generalised Lloyd algorithm: A second issue in trellis waveform coding is the design of codewords. We propose the generalised Lloyd algorithm (GLA) [1, 4, 5] for this purpose. The GLA takes the output of the encoder and computes the centroids of the source symbols coded with the same codeword. These centroids are then assigned as the new codeword values. The source is encoded again using the new codebook and the process is repeated until there is negligible improvement.

In this work, GLA and SA are run together. For a given codebook, the trellis structure is optimised using SA, and for this structure, the codebook is modified using the GLA. The process is stopped when the system reaches an equilibrium, with respect to the SA criteria.

Results: Trellis waveform coding systems of different constraint lengths were trained using a first order Gauss-Markov source, and were coded using the SA and GLA. For constraint lengths of 2–7, signal-to-quantisation-noise ratios (SQNRs) were computed. The system was then tested using another first order Gauss-Markov source. In Table 1, the computed SQNR (dB) values are given (SA + GLA) together with the results of Stewart *et al.* (GLA) [1], and of Ayanoglu and Gray (PS) [4]. Results obtained using SA are better than those of [1], especially for structures with low constraint lengths. This is expected because in Reference 1 the trellis structure was fixed, not optimised. The results obtained via the predictive system [4] are better than our results for structures with low constraint lengths. Again, this is expected because the predictive system has a higher system complexity. However, our results are sufficiently close to those of Reference 4, so that the nonpredictive system once again becomes attractive. Alternatively, SA can be incorporated into the predictive system design with possibly better performance. It is useful to compare our results with the results of Foster *et al.* [5]. As can be seen in Table 2, our results are far better than those

Table 1 SQNR (dB) VALUES

K	SA + GLA		GLA		PS	
	train	test	train	test	train	test
2	9.81	9.45	6.92	6.86	11.08	10.73
3	11.24	11.13	8.77	8.59	11.53	11.18
4	11.90	11.77	10.13	9.87	11.84	11.47
5	12.00	11.90	11.05	10.67	12.18	11.83
6	12.29	11.98	11.56	11.09	12.38	11.96
7	12.29	11.98	11.87	11.70	12.52	12.52

SA + GLA: simulated annealing and generalised Lloyd algorithm, GLA: generalised Lloyd algorithm only, PS: predictive system

Table 2 SQNR (dB) for 8 STATE TRELLIS WAVEFORM CODER AND VECTOR QUANTISERS

m	SA + GLA		VQ		FSVQ	
	train	test	train	test	train	test
1	11.24	11.13	4.42	4.40	9.21	9.14
2			7.90	7.86	11.04	10.90
3			9.24	9.17	11.22	11.08
4			10.15	10.07	11.34	11.12
5			10.56	10.47	11.61	11.26

m: vector length, SA + GLA: trellis waveform coder with simulated annealing and generalised Lloyd algorithm, VQ: memoryless vector quantiser, FSVQ: finite-state vector quantiser

obtained with vector quantisers (VQs) and finite-state vector quantisers (FSVQs). The results of Foster *et al.* who used FSVQ with vector lengths 1–3 are inferior to ours and for greater vector sizes are only slightly better than ours.

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SPACE AND WAVELENGTH FILTER FOR USE IN WDM-BASED OPTICAL SWITCHING NETWORKS

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Indexing terms: Optical switching, Optical fibres

A novel space and wavelength tunable filter is described which uses a compact, low cost electromagnetic tuning mechanism and operates from ± 5 V supplies. Prototype components show <3 dB optical loss, <1.6 dB polarisation sensitivity, channel bandwidth of >2.5 nm and adjacent channel isolation >30 dB. Channel selection is achieved in <4 ms.

Introduction: All-optical switching using WDM techniques has been suggested as offering a solution to switching bottlenecks that could occur in high speed communications networks of the future [1]. Wavelength-tunable filtering elements are a critical component in these systems, and several approaches are being investigated, including fibre Fabry-Perot filters, surface acoustic wave filters and semiconductor tunable filters [2-4]. However, future systems will require the tunable filter to select not only a particular wavelength, but also a spatial channel. The multidimensional optical network (MONET) [1] is one such system where a number of equally spaced wavelength channels are conveyed along a number of optical fibres. At periodic points on this data bus, information can be tapped off and used or rerouted. Conventionally this switching function would be implemented using an optical space switch followed by a wavelength demultiplexer or filter resulting in high optical loss and complexity.

We describe a novel space and wavelength tunable filter (SAWTR) based around a diffraction grating mounted on a compact two-axis electromagnetic tuning mechanism. The filter switches a single wavelength channel from one of an array of input fibres into an output fibre in a single operation. The filter includes an integral position sensor for closed-loop feedback control of the electromagnetic movement, giving low drift, good vibration rejection and rapid channel switching.

The current implementation has four spatial inputs carrying four wavelengths at 4 nm spacings in the 1550 nm window, but this could readily be expanded to greater numbers of spatial and wavelength channels.

Design: The principle of the SAWTR is shown in Fig. 1. Light from the array of single mode input fibres is collimated by a 25 nm focal length doublet lens onto a 600 l/mm diffraction grating mounted on the two-axis movement.

Fig. 1 Conceptual representation of SAWTR optics

After diffraction by the grating and refocusing by the lens, a two-dimensional array of spots is formed, separated by input spatial channel and wavelength. By deflecting the grating about its two orthogonal axes, any of the spots can be directed onto the multimode output fibre. In practice, the input and output fibres are all located in a single linear V groove array fabricated by silicon micromachining.

Grating movement: Fig. 2 shows a prototype two-axis electromagnetic tuning mechanism. The $12 \times 12 \times 1.5$ mm³ reflection grating is spring mounted against a central pivot pin by

Fig. 2 Grating movement on base plate

four identical stainless steel springs, allowing tilt about its centre but preventing lateral or longitudinal displacements. Two small magnets are fixed to the underside of the grating, directly above two coils mounted on the baseplate. When a current is passed through one of the coils, the corresponding corner of the grating is either attracted to or repelled from it. By adjusting the coil currents, the grating can be tilted continuously and independently about two orthogonal axes. In the prototypes the coil resistance was 30 Ω , and ± 45 mA was required for a $\pm 1^\circ$ tilt, corresponding to a wavelength range of ± 25 nm.

Because of the central pivot pin and the balanced design, the movement shows good immunity to vibration. However, to increase the vibration rejection further and to avoid problems of drift, integral angle sensing and feedback control electronics have been developed. This has the further benefit of improving the speed of response.

Angle sensing and control: Grating angle sensing is achieved using an optical sensor. A rod lens is fixed to an 850 nm LED