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3 × 3 ALL-FIBRE ROUTING SWITCH

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Abstract

An all-fibre acousto-optic switch has been constructed from a 3×3 null fused coupler. The maximum drive power required is 4 mW, the switching time is 100 μs and the insertion loss is less than 0.5 dB. The switch shares the advantages of an earlier 2×2 switch but with more fibre ports, and should permit the design of compound routing arrays with fewer switching elements per channel.

In a previous paper, we have described a 2×2 acousto-optic switch made from standard single-mode fibre[1]. The switch is based on a special "null" fused taper coupler that does not couple any light when passive; light is only coupled when a suitable flexural acoustic wave is imposed on the structure. Compared with existing technologies, the switch offers advantages of very low insertion loss (of the order of 0.1 dB or less), low drive power ($\sim$ 1 mW) and a fast switching time ($< 100\ \mu s$). Its simple monolithic construction avoids the need for collimation optics or the attachment of pigtails, and gives the potential for low cost. The most significant potential application is as a routing component in optical fibre telecommunications. Compound switches with many fibre ports can be built up from interconnected arrays of 2×2 switching elements[2]. However, savings could clearly be made if the switching elements themselves had a greater number of ports, so that fewer would be needed to construct the required array. Since fused couplers can be made with more than four ports, we investigated the possibility of constructing an acousto-optic switch using a 3×3 fused coupler.

As with the 2×2 switch, the 3×3 coupler must be a null coupler. That is, when light is launched into one of the input fibres, it excites just one mode of the cladding-air waveguide at the narrow waist of the coupler. The mode propagates along the waist without change, and the light then returns to the same fibre at the output end[1]. Each fibre has a different mode associated with it in the waist. To give this behaviour, the three initially identical fibres from which the coupler is made must be made dissimilar by heating and stretching (pretapering) two of them by different amounts, before they are elongated together to form the coupler[3]. To couple light from one fibre to another, a flexural acoustic wave with a wavelength matching the beatlength between the appropriate pair of modes in the waist must be present.

The behaviour of any multiport fused coupler device depends critically on the cross-sectional arrangement of the fibres. For a null coupler made from three fibres arranged in a straight-line array, the modes corresponding to each fibre (Fig. 1) can be deduced by assuming that the taper transitions are strictly adiabatic, with the proviso that each mode's field distribution must be symmetric about the plane of the fibres. This is because the light waves in the fibre ports, as well as the structure itself, are mirror-symmetric in this plane. Thus light in the widest fibre excites the LP_{01} fundamental mode in the waist. Light in the intermediate fibre excites one of the LP_{11} second modes, and light in the narrowest fibre excites one of the LP_{21} third modes; in both cases, the mode that is excited is the one that is symmetric about the plane of the fibres. (Of course, the fibres only differ in the vicinity of the coupler - far from the coupler, they are identical.) For symmetry reasons, no fundamental flexural wave can couple light between the LP_{01} and LP_{21} modes, so light cannot be routed directly between the widest and narrowest fibres. However, acousto-optic coupling can occur between either mode and the LP_{11} mode; light can be routed between the intermediate fibre and either of the others. Thus the device is a 3×3 switch with the restricted set of allowed states shown in Fig. 2.

Since the two relevant beatlengths are different, acoustic waves of different frequencies are required for the two cross states. The frequency f_{01} for switching to the widest fibre is just the same as for the simpler 2×2 switch[1], because the same two modes (LP_{01} and LP_{11}) are involved. It can be shown that the frequency f_{21} for switching to the narrowest fibre, for the same wavelength of light, is given by

where U_{j1} is the core parameter[4] for the LP_{j1} mode. This ratio is 1.73 for a circular coupler waist and 2.78 for a rectangular waist (also strongly fused), assuming that the three modes waist and 2.78 for a rectangular waist (also strongly fused), assuming that the three modes are far from cut-off. Thus the ratio of frequencies depends strongly on the cross-sectional shape of the waist. The acoustic amplitude must also be adjusted for maximum coupling. More acoustic power is required to achieve this at the higher frequency; for a circular waist, the ratio of powers is about 1.7.

We made a 3×3 null coupler using standard single-mode telecommunications fibre with a diameter of 125 μm and a cut-off wavelength of about 1200 nm. Two of three lengths of fibre were initially pretapered to 90 μm and 60 μm respectively along a 40 mm length. The three fibres were then held in parallel contact and heated and stretched to form the coupler. Uniformity and diameter control were achieved by using a travelling flame as the heat source. The final coupler had a circular waist with short taper transitions. The excess loss of the passive coupler was 0.22 dB and the maximum power coupled from any fibre to any other fibre was 1:400, indicating that it was a good null coupler. The acoustic wave was generated using a PZT disc driven by an RF electrical supply. The wave was imposed on the coupler via a conical aluminium horn, the tip of which was bonded to an unstretched fibre port[1]. The diameter was chosen so that the resonance conditions between the intermediate fibre and both of its neighbours could be satisfied by the same transducer.

Light from a 1550 nm DFB laser was launched into the intermediate (90 μm) fibre via a suitably adjusted polarisation controller. Light could be coupled to the widest (125 μm) and narrowest (60 μm) fibres for acoustic frequencies of 0.8 MHz and 1.6 MHz respectively. The optical powers emerging from the two coupled output ports as a function of pk-pk voltage applied to the transducer are shown in Figure 3. Figure 3a is for light acoustooptically coupled to the 125 μm fibre at 0.8 MHz, with a maximum conversion efficiency of 94 % when the supplied RF drive power was 2 mW. Figure 3b is a similar curve for light coupled to the 60 μm fibre at 1.6 MHz, with a maximum conversion efficiency of 97 % when the drive power was 4 mW.

The time response of the switch was measured by modulating the RF drive with a slow square wave, and the results are given in Figure 4. The time lag between the RF signal and the start of switching is the time the acoustic wave takes to travel from the transducer through the horn and along the fibre to the coupler. Light then transfers as the acoustic wave propagates along the coupler waist. The net effect in both cases is a delay of about 130 μs between the electrical signal and the completion of optical switching.

Larger values of maximum coupling, and hence better channel isolation, would be expected by using a more broadband acoustic transducer and closer polarisation control. The experimental value of 2 for the ratio of the drive frequencies lies between the theoretical values for circular and rectangular cross-sections. By cleaving the coupler waist, it was found that the cross-section was indeed an intermediate oval shape. We therefore consider that the ratio of 2 is not fundamental, but is merely a coincidence arising from the particular coupler used. The coupled light is frequency shifted by an amount equal to the acoustic frequency. However, a frequency shift of around 1 MHz is insignificant in a telecommunications routing switch, even when several are concatenated.

We have demonstrated the operation of an all-fibre 3$\times$3 acousto-optic switch, which has the same advantages as the earlier 2$\times$2 switch but with extra ports. Switches with even more ports should also be possible. Optical routing arrays are usually designed with 1×2 switching elements in mind. The availability of efficient monolithic 1×3 (and higher-order) switching elements should prompt the design of new array topologies with fewer elements per channel.

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References

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4. A. W. Snyder, J. D. Love: *Optical Waveguide Theory*, Chapman and Hall, London (1983).

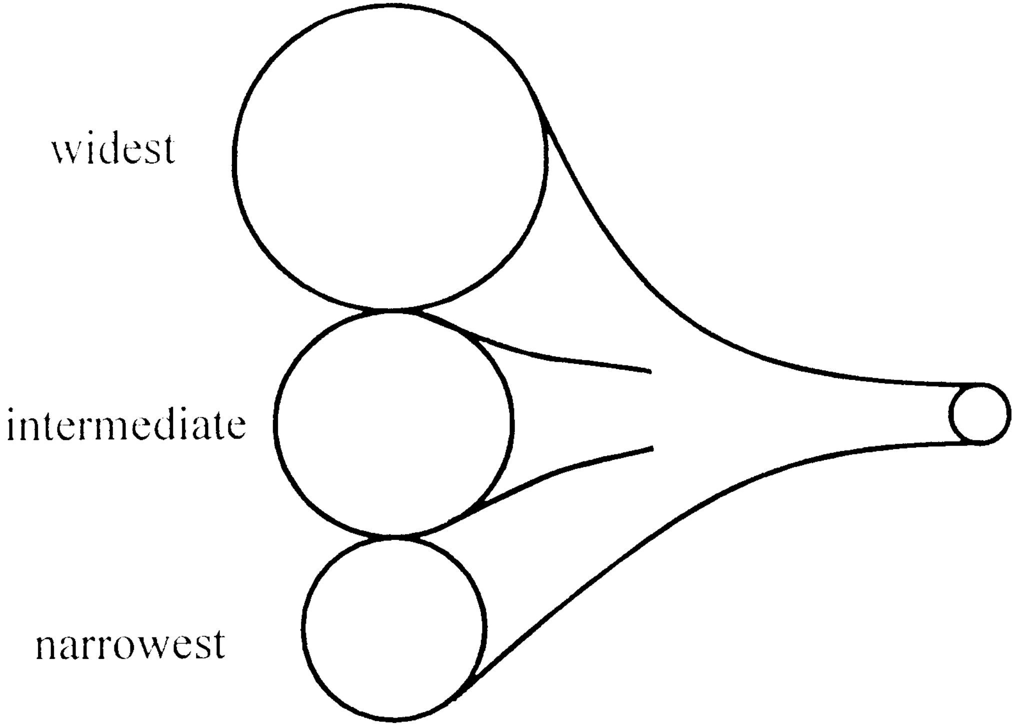
Figures

1. A schematic illustration of (a) the structure of one half of the 3×3 null coupler, and (b) the modes excited in the coupler waist by light waves in each input fibre.

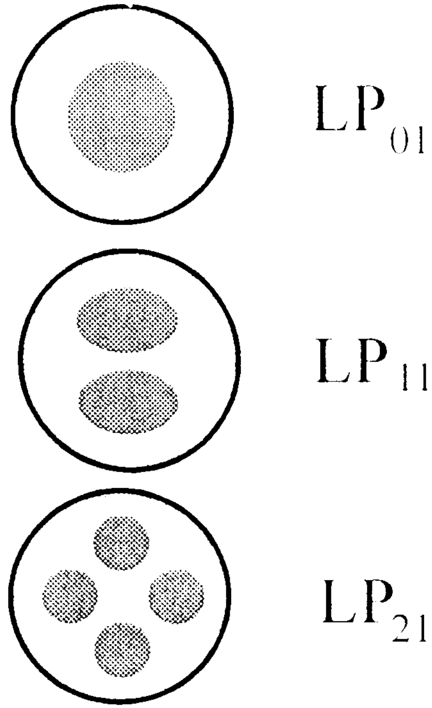
2. The three possible states of the switch: (a) bar state (no acoustic wave); (b) first cross state (acoustic wave at lower resonant frequency); (c) second cross state (acoustic wave at upper resonant frequency).

3. Optical output powers versus RF drive voltage, for input light in the 90 μm fibre. The hollow points represent the power remaining in the 90 μm fibre, while the solid points represent the power coupled to (a) the 125 μm fibre for an acoustic frequency of 0.8 MHz, and (b) the 60 μm fibre for an acoustic frequency of 1.6 MHz. The output in the remaining fibre in each case was less than 1 % at all times. The RF drive powers for maximum coupling are 2 mW and 4 mW respectively.

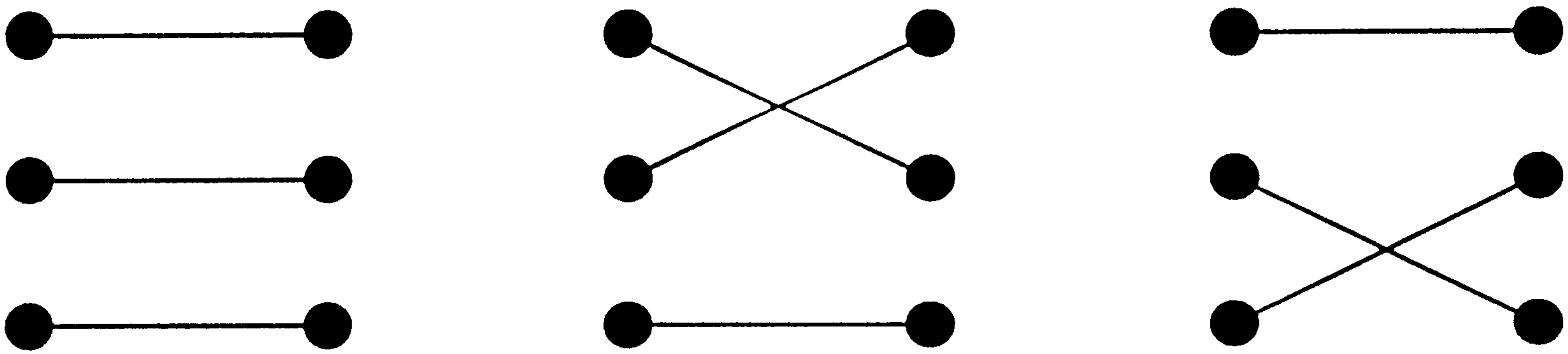
4. The time variation of the throughput and coupled optical output powers for coupling to (a) the 125 μm fibre at 0.8 MHz and (b) the 60 μm fibre at 1.6 MHz. The RF drive is turned on at $t = 0$.



a)

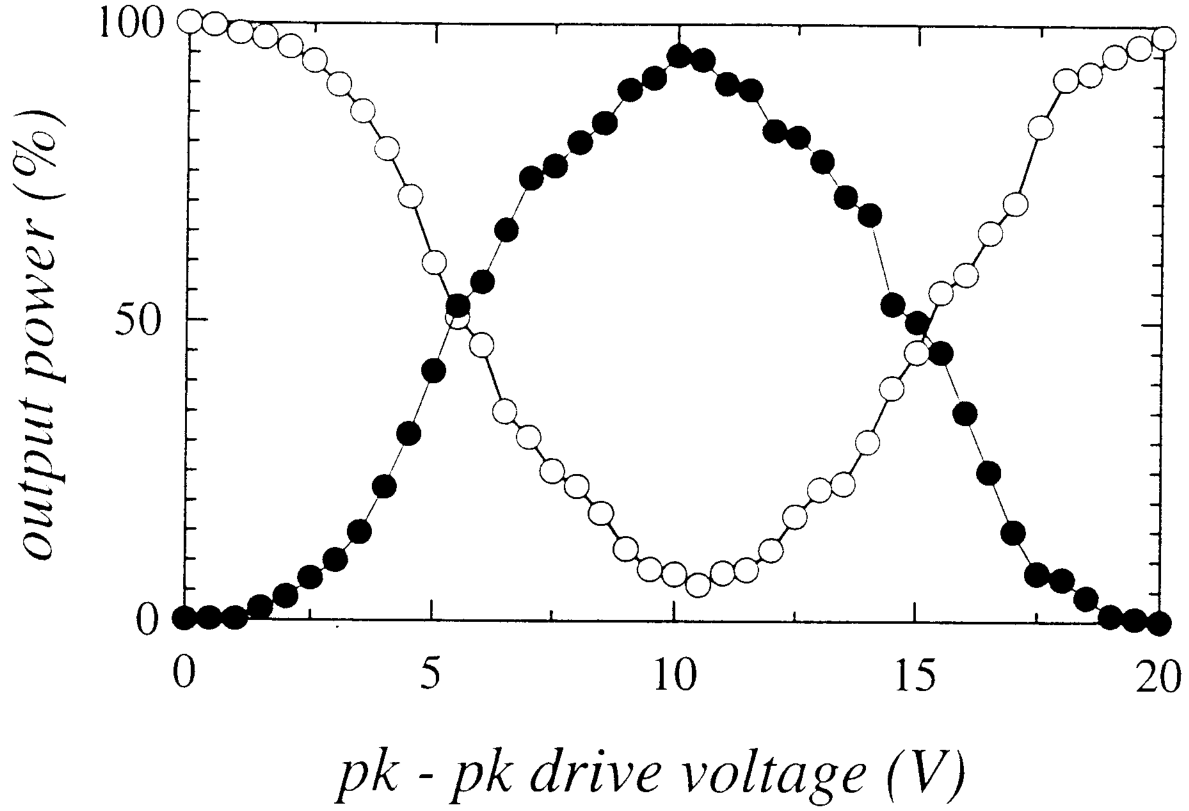


b)



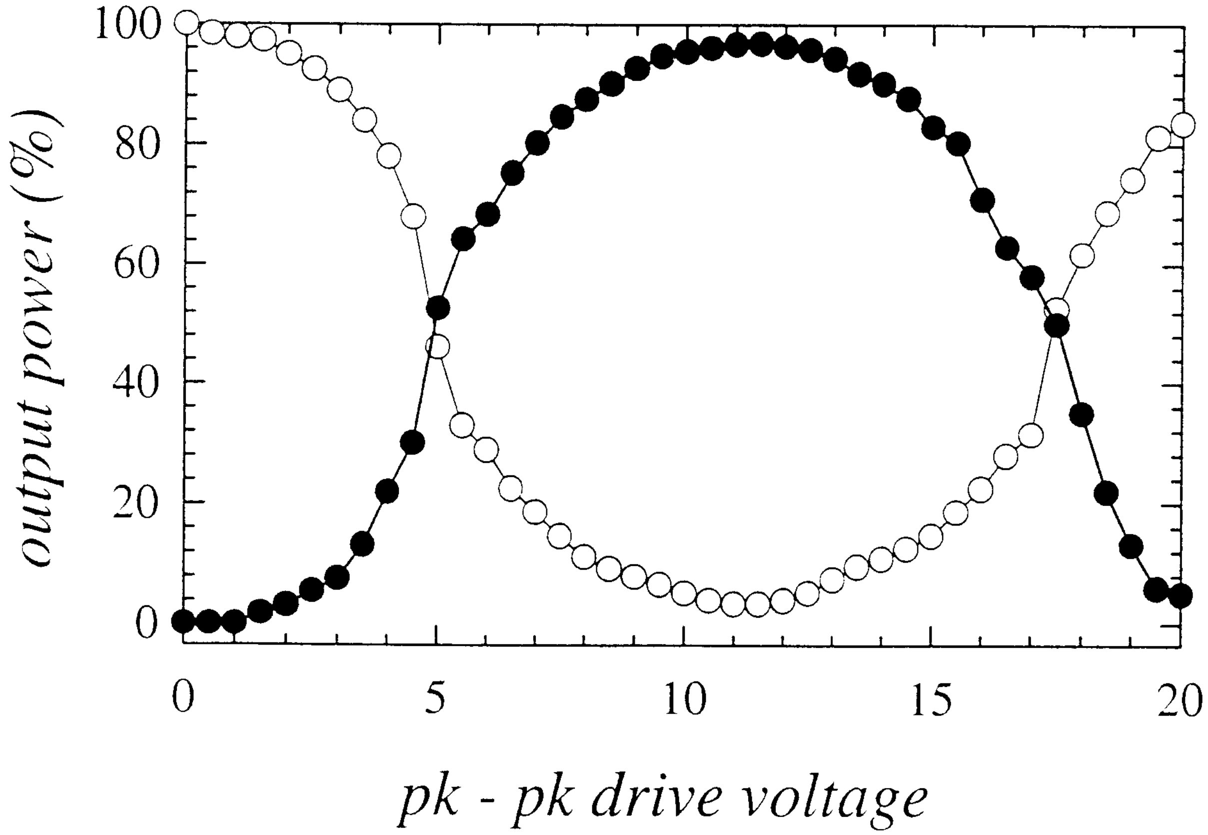
(a) (b) (c)

a)



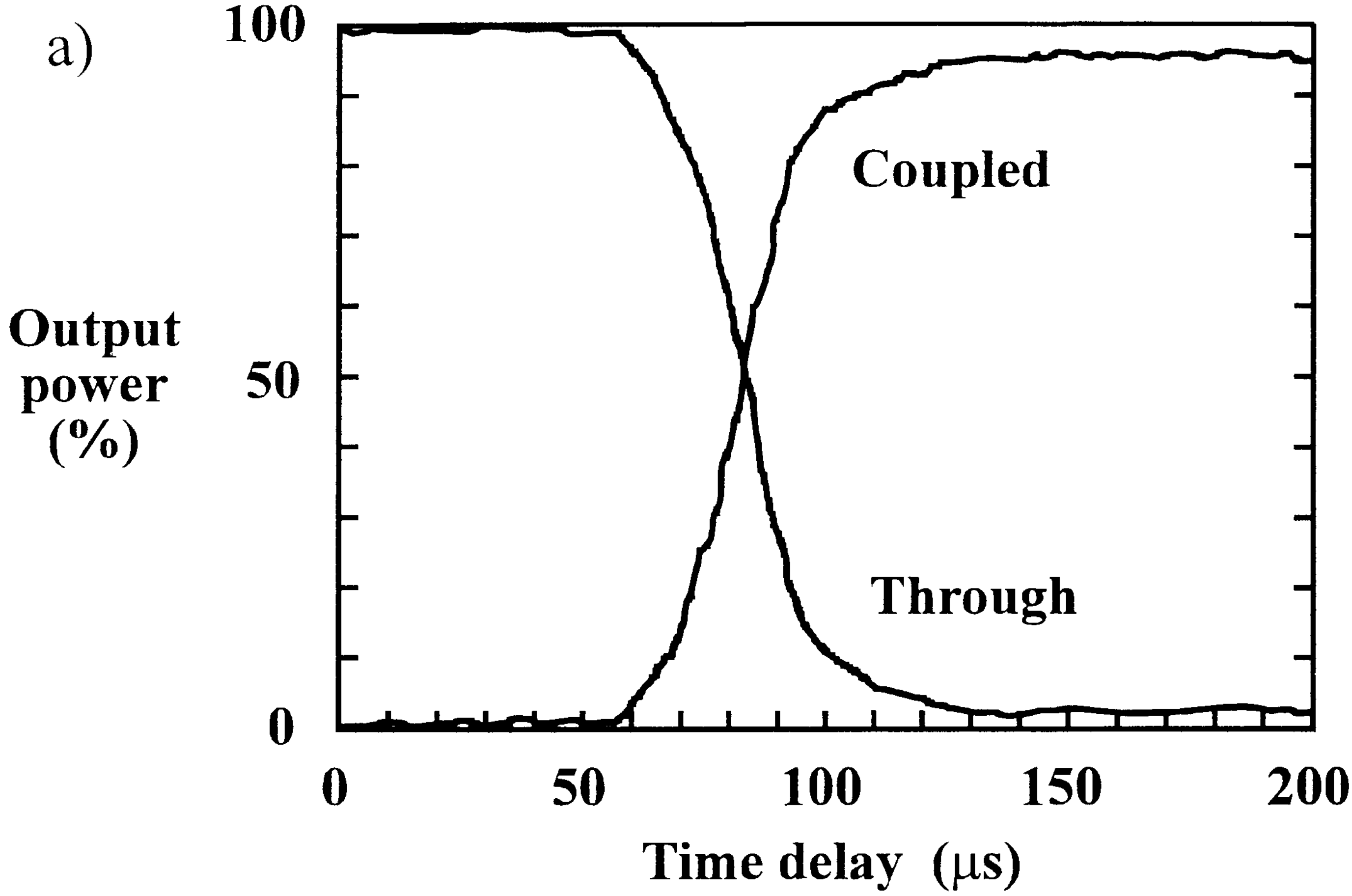
100
50
0
output power (%)
0
5
10
15
20
pk - pk drive voltage (V)

b)

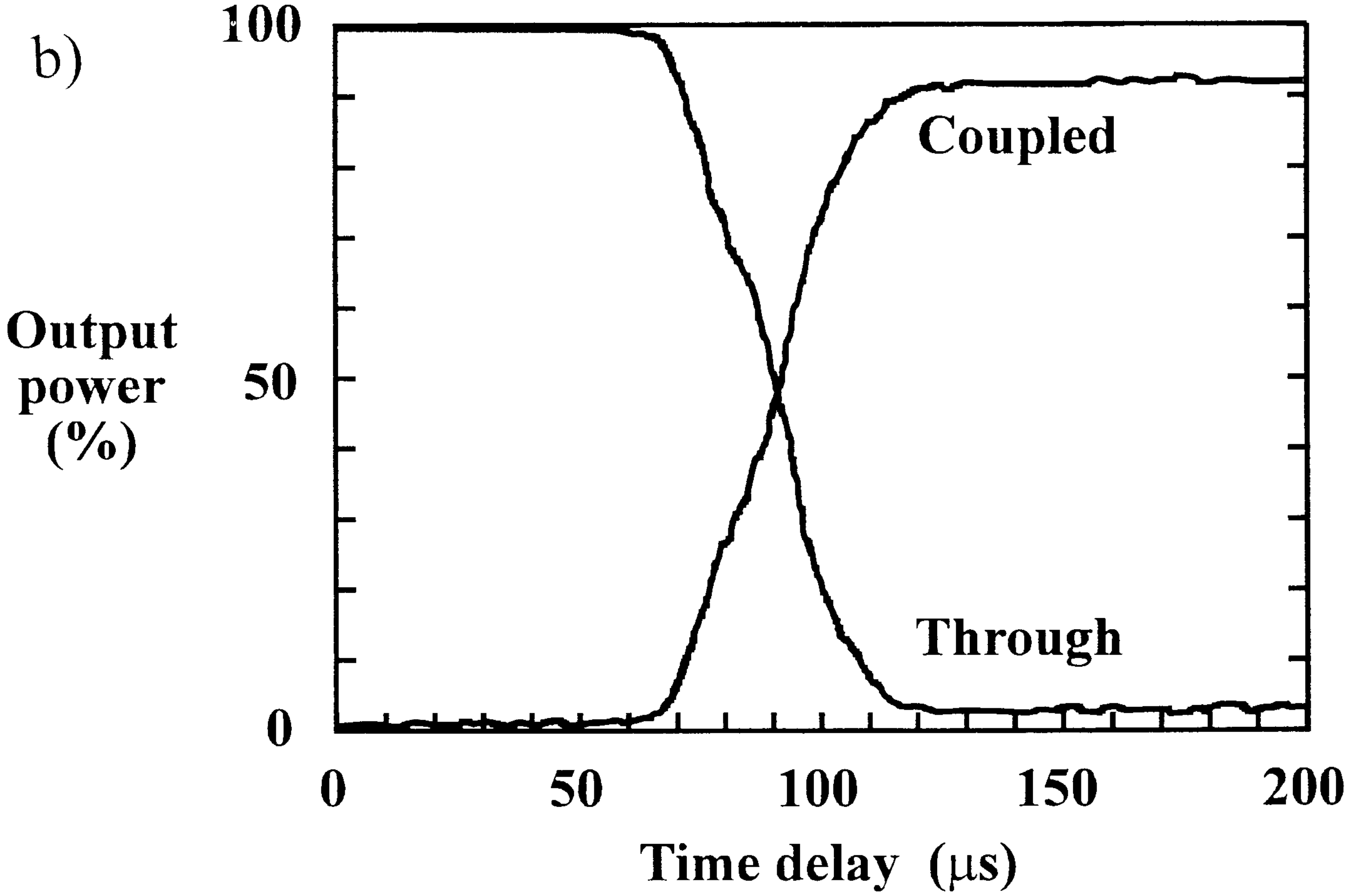


100
80
60
40
20
0
output power (%)
0
5
10
15
20
pk - pk drive voltage

a)


100
50
0
Output
power
(%)
Coupled
Through
0
50
100
150
200
Time delay (μs)

b)


100
50
0
Output
power
(%)
Coupled
Through
0
50
100
150
200
Time delay (μs)