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Experimental study of the response of a bad cavity bistable system to fast light switch-on

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Preliminary results are reported on the response of an intrinsic bistable system to the rapid switch-on of an injected light field. The bistable system consists of a linear array of 25 sodium atomic beams contained in a low finesse Fabry–Perot etalon. The beams are aligned perpendicular to the direction of propagation of the cavity field and are collimated sufficiently to resolve the D-line ground state $3^2S_{\frac{1}{2}}$ hyperfine structure.

The etalon conditions are such that the cavity lifetime is an estimated 6 ns compared with the atomic lifetime of 16 ns; hence the system approaches the bad cavity limit in which the atom dynamics should be observable.

The radiation from a single-mode ring dye laser is switched on to the bistable system in approximately 1 ns. Although preliminary results show low branch to high branch switching there is no evidence of the expected nutational oscillations.

1. Introduction

One aspect of optical bistability that has received scant experimental attention is that of the spectrum. An interesting feature of an intrinsically bistable system consisting of an optical cavity with an atomic medium is the prediction that the fluorescence from the low branch would be single-peaked while that from the upper branch would exhibit the three peaks of the dynamic Stark effect (Bonifacio & Lugiato 1976; Carmichael & Walls 1977). To do an experiment where the fluorescent spectrum was analysed would be technically difficult, owing to the high degree of frequency stability required of the laser and optical cavity over a long period of time. However, the three-peaked spectrum has a corresponding feature in the time domain. If radiation with intensity above the threshold for a three-peaked spectrum is suddenly switched on, the response of an atomic medium on resonance is to produce a coherent optical transient oscillating at the Rabi frequency, i.e. the frequency of separation of the central fluorescent peak from its two sidebands. This has been demonstrated for sodium atoms in a vapour by MacGillivray *et al.* (1978).

Numerical simulation by Bonifacio & Meystre (1978) and Abraham & Hassan (1980) of the response of an optically bistable system that is stepwise excited to the upper branch indeed verified the existence of the Rabi oscillations in the Maxwell–Bloch model. The conditions of the calculation required the cavity lifetime, t_c, to be very much smaller than T_1 and T_2, the atomic population and dipole relaxation times, respectively. This is the so-called 'bad cavity' limit. The first attempts to observe this transient phenomenon are reported here.

Recently, the 'good cavity' limit case, where the cavity lifetime is dominant, has been studied experimentally by Grant & Kimble (1983).

2. The experiment

An abridged schematic diagram of the apparatus is shown in figure 1. The Fabry–Perot etalon mirrors are flat and have a reflectivity of approximately 93 %. The cavity tuning is controlled by a set of driven piezo-ceramics mounted on one mirror. A ring cavity is constructed by the addition of one 100 % reflecting flat mirror. The empty cavities have a free spectral range of approximately 750 MHz and a finesse of about 10. So t_c is estimated to be 6 ns.

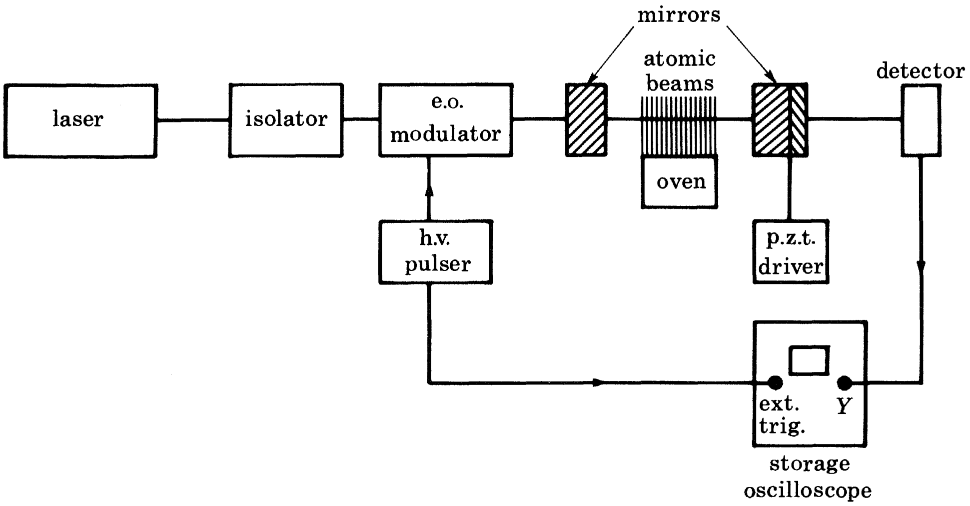

Figure 1. Experimental configuration: e.o., electro-optic; h.v., high voltage; p.z.t., piezoelectric.

The cavity medium consists of a linear array of 25 atomic beams of sodium. Unlike the experimental arrangements of Weyer *et al.* (1981) and Grant & Kimble (1983), high collimation of the atomic beams is not possible since greater absorption in the medium is required than in their experiments. This is to maintain the system in a bistable condition as described by the bistability coefficient

$$C = \alpha l F / 2\pi.$$

That is, a decrease in the finesse of the cavity must be compensated by an increase in the absorption in the medium. The D lines are being investigated and the atomic beam collimation is just sufficient to resolve the transitions associated with the two hyperfine levels of the $3^2S_{\frac{1}{2}}$ ground state. This resolution is necessary to remove the condition for creating a non-absorption resonance in the Fabry–Perot system as observed by Schulz *et al.* (1983), when sodium vapour was used as the cavity medium.

The radiation source is a Spectra Physics 380D actively stabilized ring laser pumped by a 171 Ar^+ laser. Up to 200 mW of power is available at the input port in a collimated beam of just greater than 1 mm diameter.

The electro-optic device acts as a switch capable of making square pulses of light variable between 5 ns and 500 ns long with rise-times of about 2 ns. The leading edge of the driving pulse triggers the oscilloscope for a transmission against time plot.

The light transmitted by the cavity is detected by a PIN photodiode. The data is recorded photographically from the storage oscilloscope.

3. Results and discussion

Figure 2*a* is the transient response of the atomic medium to the rapid switch on of the radiation. There is no cavity in this case. Fifty milliwatts of linearly polarized light was injected, tuned to the $F = 2 \rightarrow F'$ hyperfine transition of the D_2 line. An almost identical result was obtained for the $F = 1 \rightarrow F'$ transition. The Rabi oscillations are clearly evident with a frequency of approximately 200 MHz.

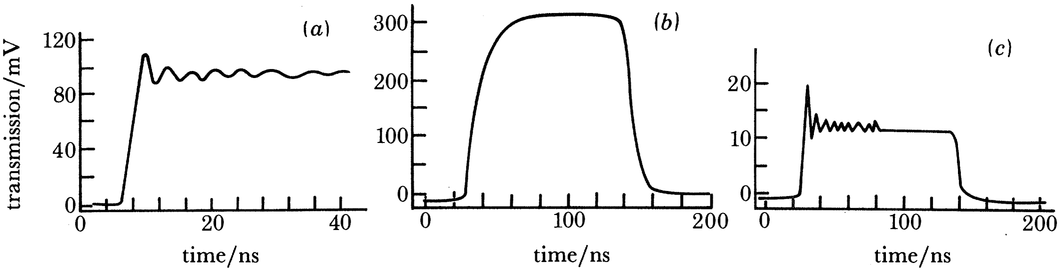

Figure 2. The transient response of (*a*) the atomic medium (*b*), (*c*) the empty cavity. The transmission is in units of detector volts. For (*c*) the cavity frequency has been detuned from that of the injected light.

The response of the resonant, empty Fabry–Perot etalon to a similar stepwise change in the injected intensity is shown in figure 2*b*. The cavity filling time of approximately 20 ns (0–90 %) is consistent with the lifetime $t_c = 6$ ns (Grant & Kimble (1983), equation 3). If the cavity is detuned, a transient oscillation occurs due to the interference of non-phase-matched cavity fields, which have completed different numbers of round trips (figure 2*c*). The frequency of this oscillation increases with detuning. Similar results to these were obtained with the ring cavity.

Figure 3 shows the response of the atom-filled cavities to the rapid switch on in intensity. The laser is tuned to the D_2 line and to the frequency that gives the optimum hysteresis for a slow intensity cycle. The varied parameter in figure 3 is the cavity frequency. The data is interpreted in the following way. In figure 3*a* the Fabry–Perot is detuned from the bistable region. The oscillations are those observed previously in the empty cavity since they increase in frequency with further cavity detuning, whereas a Rabi oscillation would decrease in frequency due to the lowering of the effective cavity field. Figure 3*b* illustrates switching from the low branch to the high branch as the cavity is 'pulled' into resonance by the changing refractive index of the atomic medium. Figure 3*c* depicts the same phenomenon for the cavity with greater initial detuning. Essentially the same behaviour is evident in the ring cavity (figures 3*d*, *e*, *f*).

There is no indication of Rabi oscillations. The cavity intensity is estimated to be 150 mW so that the effective Rabi frequency should be less than 400 MHz, which is within the bandwidth of the detector equipment.

The most plausible reason for the non-appearance of the Rabi oscillations is that the light field inside the cavity is not switching on fast enough to obtain a coherent transient. From figure 2*a* it can be seen that the nutations from the atomic beams alone have decayed away in approximately 15 ns.

There are two options for the pursuit of these oscillations. Either a lower finesse cavity will

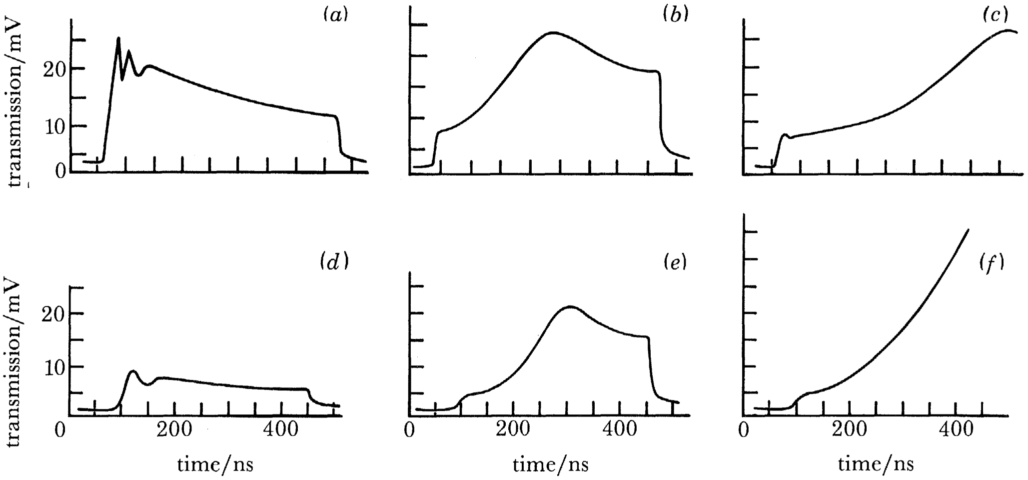

FIGURE 3. The transient responses of the bistable system: (*a*)–(*c*) for the Fabry–Perot etalon; (*d*)–(*f*) for the ring cavity. The transmission is in units of detector volts. In each sequence the cavity frequency is the varied parameter.

have to be manufactured with, subsequently, a faster cavity filling time, or an atomic system with a longer lifetime will have to be used. The problem associated with the first alternative is that if the finesse is too low a bistable condition may become impossible to attain.

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