Chapter 1

Introduction

When a blue-detuned, intense, near-resonance laser beam propagates through a dense atomic vapor a diffuse ring of light may be observed around the central laser spot in the far field. This phenomena has been referred to as conical emission or cone emission (CE) in the literature. CE has been observed from ns pulses and continuous wave (cw) beams in atomic vapors (sodium [43, 41, 10, 37, 28, 22, 21, 17, 47, 49, 11], potassium [24], barium [9, 14, 44, 48, 8], cesium [48], calcium [19], and strontium [6, 26]), and also from ps and fs pulses propagating through glasses [2]. CE from glasses has been observed in the presence of laser beam self-focusing, and it appears to be reasonably consistent with four-wave-mixing (FWM) in a homogeneous medium [42]. The red-detuned and blue-detuned side-bands are presumed to result from Stokes and anti-Stokes Raman transitions and both side-bands emerge at cone angles related to FWM phase matching. The glass medium is presumed to be weakly saturated, sufficient to confine the self-focused beam but not to significantly modify the index of refraction variation versus wavelength. In atomic vapors CE is normally, but not always [10, 37, 26, 7], observed with blue laser detuning, and this can also yield self-focusing. FWM of Rabi side-bands has often been used to explain CE from atomic vapors, and the only cw experiment appears to be well explained by a calculation that combines this with an inhomogeneously saturated medium, due to a self-trapped laser beam [50]. But when atomic vapors are illuminated with ns pulsed lasers there is a problem with this explanation, because the fourth wave is not observed, **i.e.**, the blue-detuned Rabi side-band required for FWM is missing from the emission [26]. The CE occurs on the red side of the atomic line and emerges at about the angle represented by either a phase-match condition or refraction at the boundary between a saturated and unsaturated medium. This has led to the suggestions of a Cherenkov type process (phase matching) [21, 4, 55] or Rabi side-band generation in the saturated region and boundary refraction [27]. However, these suggestions do not solve the problem of the missing side-band, and they are also inconsistent with other features of the full angular spectrum [26]. Thus, although scores of calculations have been published regarding this phenomena, even the most basic questions regarding the causes and behavior of pulsed CE generation in atomic vapors have not been definitively answered.

In essentially all experiments, CE is only observed once the laser has induced a significant radially varying saturation in the medium, which also produces self-focusing. Thus, the generation of CE appears to be intimately connected to a radially varying beam intensity, and in the calculation that explains the cw experiment this is indeed a key feature in the model [50]. In that experiment, as well as the pulsed experiments, a very significant saturation of the atomic transition occurs under conditions that yield CE. This causes major modifications of the FWM gain and phase matching angle, index of refraction and Rabi side-band frequency, all of which become functions of radius and time within a pulse. No models for pulsed CE emission have attempted to include these complications, so the absence of a clear explanation for the transient experiments is not surprising. However, this is a formidable problem and experimental guidance is definitely called for.

A serious difficulty arises in interpreting previous pulsed CE experiments in atomic vapors. It appears likely that in all cases where CE has been observed the incident laser beam has broken up into many self-trapped filaments that propagate separately through the vapor. Beam break-up has been observed in many experiments [43, 41, 10, 37, 24, 44, 6, 26, 27], and our measurements of break-up versus laser beam and vapor parameters suggest that the conditions of other CE experiments have probably been in this break-up regime. (Some papers do not contain all the information required to test this issue.) When beam break-up occurs, the laser beam intensity distribution and the actual intensity felt by the atoms are unknown. Also, the intensity within each filament is generally not proportional to incident laser power. The next problem with data from an experiment that includes beam break-up is that, during rearrangement into a packet of self-trapped filaments, portions of the laser beam propagate at large angles to the cylindrical propagation axis. Thus, there is always the question of whether the cones were formed during break-up. Other uncertainties regard the unknown effect of the overlapping wings of self-trapped filaments and the possibility that they oscillate in radius during propagation. Needless to say, no theories or models have considered more than one isolated laser beam with a smooth, monotonic intensity, $\mathrm{I}(\tilde{r})$[1] , that propagates without oscillations. Yet another uncertainty that results from beam break-up is extremely important. The phase-propagation velocity of a self-trapped beam is a sensitive function of beam power and radius; it varies from c to c/n where c is the speed of light and n is the index of refraction of the unsaturated medium at the laser frequency [45, 12, 15, 16, 30, 32, 46, 52]. The cone angles calculated with a FWM, boundary-refraction, or Cherenkov model all depend on the differences between the phase velocities of the cone emission versus the laser, yet the latter is essentially unknown in beam break-up experiments.

For the reasons given in the previous paragraph, the present experiment measures CE from a single, pulsed, self-trapped filament of light propagating through an atomic vapor. We adjust the incident laser radius and power to near the values that yield a single, stably propagating, self-trapped filament, thereby minimizing radial oscillations during propagation. We verify the self-trapping of the pulsed beam by imaging the beam as it exits the cell. Previous theories or explanations of pulsed CE have assumed that the laser phase velocity (v_l) is either c or c/n, but as noted above it actually varies between c and c/n as the filament parameters vary. This velocity, which is independent of $\tilde{r}$, is crucial to evaluating the cone angle. By varying laser beam parameters, we have been able to study CE across essentially the entire c to c/n range of (v_l), while maintaining approximate knowledge of this velocity.

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[1] The symbol $\tilde{r}$ will be a radial measurement with units where r will be a dimensionless radial measurement