the near future, we plan to use a different experimental system in order to demonstrate higher bandwidth. Specifically, we will use a Silicon Nitride waveguide, embedded in a cell containing Rb vapor as well as high pressure Ethan buffer gas. The core technology for such a system has already been demonstrated [34]. This system has the property that, just like in the case of the TNF, the evanescent field that interacts with the atoms can produce a very high intensity at a very low power. Furthermore, unlike in the case of the TNF, the interaction length can be made very long. One of the drawbacks of the system is that, in its current incarnation [34], the power throughput is very small due to inefficient input coupling. This problem can be circumvented by using a tapered section at the input, or using a photonic crystal based coupler.

It should be possible to realize this modulator at a telecommunication wavelength at very low control powers using the tapered nano fiber (TNF) set-up [10], employing the $5S_{1/2}$-$5P_{3/2}$-$6S_{1/2}$ system, for which the probe transition is at ~1367 nm. The TNF needs to be designed to operate as a single mode fiber for both wavelengths: 780 nm and 1367 nm. We have carried out designs of such a TNF, and have shown that there is a range of taper diameters for which it is possible to have a significant overlap between the evanescent modes at these two wavelengths. The TNF would be embedded in a Rb vapor cell, and pressurized with Ethane buffer gas. The pump and the probe will be combined using a dichroic mirror and launched into the TNF. As a figure of merit (FOM) for implementation in our TNF system, one can use the number of photons in the pump field that are needed to switch the state of the probe from 'off' to 'on'. In order to achieve an intensity equivalent to a free space pump power of 1W for a spot size of 50μm, the TNF system with a mode area of 0.2 μm^2 would require a pump power of ~80 μW. Assuming a rise time of 2.5 nS for operation at a modulation speed of 200 MHz, the number of pump photons at 780 nm needed for switching would be $\sim 5*10^5$. Of course, a telecom wavelength modulator of this type can also be realized using the SiN waveguide approach discussed above. Allowing for a near unity throughput using one of the configurations (e.g. tapered waveguide section or a photonic crystal at the input) mentioned above, a bandwidth of 32 GHz for the same power level would correspond to an FOM of $\sim 3*10^3$. Of course, to achieve high modulation depth while using the same power, the interaction length (and hence the optical density) has to be much longer than that of the TNF (which is only about 1 cm). As mentioned above, this is easy to achieve for the waveguide, even within the constraint of a small chip, by using smoothly folded patterns [34]. As a comparison with other techniques for low power all-optical modulation [21–24], we find that the instability induced switch has an FOM of $4*10^4$ photons [19] while micro-ring resonators based switches have an FOM of $4*10^7$ photons [20]. Thus, this approach is a potentially attractive option for low power all-optical modulation.

7. Conclusions

To conclude, we demonstrated a novel high speed all-optical modulator using the 5S-5P-5D transition. We homogeneously broadened the transitions by making use of collisional broadening and fine structure mixing induced by high-pressure buffer gas of Ethane. We obtained a bandwidth of ~200 MHz, which represents a 100-fold increase in the bandwidth, in comparison to a system without buffer gas. The observed bandwidth is within a factor of 2.5 of what one might expect based on the parameters used in the model of the system we have employed, and is limited by various practical constraints in our experiment. We also present numerical simulations for the system and predict that a modulation speed of as much as 32 GHz should be achievable under suitable conditions, using a SiN waveguide embedded in a buffer-gas loaded Rb vapor cell, using only about 80 μW of power.

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