Abstract—Spectral properties of photonic crystal double-heterostructure resonant cavities were investigated using the three-dimensional finite-difference time-domain method. Bound state formation associated with dispersion minima is observed as well as Fabry-Perot resonances associated with the waveguide cladding.

I. INTRODUCTION

Two-dimensional planar photonic crystals (PCs) are a candidate for optical integrated circuits due to their versatility and small size. Recently the PC double-heterostructure (DH) cavity has received attention due to its very large quality factor (Q) and its potential for integrability with PC components. In this report, we investigate the spectral properties of several PCDH devices using the three-dimensional finite-difference time-domain method and compare the results where possible with our experimental data. Specifically, the identification of bound state frequencies near points of zero group velocity in the PC waveguide (PCWG) dispersion is made. Furthermore, Fabry-Perot resonances associated with PCWG dispersion adjacent to the corresponding group velocity zeros (GVZs) are observed. In addition, it was observed that out of plane radiation can be reduced by arranging the DH such that an odd number of PC holes are adjacent to the waveguide core.

A typical PCDH cavity is depicted in Fig 1. From the figure, it can be seen that the double heterostructure is formed by perturbing the lattice constant by 2.5% of an otherwise single line defect (W1) triangular PCWG. For the device shown, the air-clad membrane has a thickness to lattice constant ratio, d/a, of 0.6 and a hole radius to lattice constant ratio, r/a, of 0.3. The lattice constant for a device operating near 1550 nm typically falls in the range of 380nm – 420nm. Material parameters used were consistent with the InGaAsP material system.

The computational domain is especially large due to the need for long unperturbed waveguide sections on either side of the DH. In this study 40 unperturbed PCWG periods were placed on either side of the perturbed 2-3 periods making up the DH. The algorithm is parallelized on 192 processors running for 16 hours. The resulting time sequence is Fourier transformed, and the Pade interpolation is employed to measure spectral peak widths and center frequencies accurately. Time-domain filtering is used on subsequent program runs to analyze spatial field profiles associated with different resonances.

II. BOUND STATE FORMATION

Figure 2a displays the first Brillouin zone of a single line defect PCWG dispersion diagram, and Fig 2b shows spectra associated with DH cavities formed by both increasing and decreasing the lattice constant by 2.5%. It can be seen that high Q resonances are formed around center frequencies associated with GVZs in the PCWG dispersion diagram. Calculated Q values in the range 300K-500K have been found for the mode at normalized frequency 0.265 which is consistent with numbers measured experimentally.

When the GVZs are concave up (down), increasing (decreasing) the lattice constant in the defect region creates the bound states. This is expected, because the PCWG dispersion diagram scales inversely with the lattice constant, so that increasing (decreasing) the lattice constant shifts the corresponding frequencies down (up). Figure 3a displays the spatial Fourier transform of the PCDH bound state at normalized frequency 0.287 and illustrates Fourier components near the Brillouin zone boundary in the x-direction. In Fig 3b, the Fourier components of a PCDH with...
-2.5% defect are located at $\beta_n = 0.6 \pi$ consistent with the GVVZ with downward curvature in the dispersion diagram. In this case the calculated $Q$ is 1049. This lower value is a result of its proximity to the light cone.

Figure 3. Spatial Fourier transforms of (a.) resonant mode at 0.287 normalized frequency for a +2.5% PCDH cavity, (b.) resonant mode at 0.297 normalized frequency for a -2.5% PCDH cavity.

In Fig 2b both the positive and negative defects produce a series of peaks in the spectral ranges 0.265-0.280 and 0.288-0.297. Inspection of the PCWG dispersion diagram in Fig 2a shows that PCWG propagating modes exist in these frequency ranges. Measuring the peak spacing and solving for the corresponding frequency dependent index of refraction for Fabry-Perot oscillations in the PCWG sections adjacent to the cavity is in good agreement with what is expected from the group velocity calculations of plane PCWGs without the heterostructure. A comparison of the group indices is shown in Fig 4a. The shift between the group indices obtained from the heterostructure spectrum and those obtained from a finite-element PCWG calculation is attributed to slight differences in the material indices of refraction used in the two calculations. Fig 4b shows a comparison between a calculated spectrum and data obtained experimentally. Lasing was observed at the frequency associated with the bound state at the normalized frequency of 0.297.

IV. CONCLUSION

In summary, we have analyzed spectral properties of air-clad PC double-heterostructure resonant cavities and identified bound state formation near group velocity zeros, identified Fabry-Perot resonances and illustrated controllability of peaks and nulls in the spatial field profile.

ACKNOWLEDGEMENT

This study is based on research supported by the Defense Advanced Research Projects Agency (DARPA) under contract No. F49620-02-1-0403 and by the National Science Foundation under grant ECS-0094020. Computation for the work described in this paper was, in part, supported by the University of Southern California Center for High Performance Computing and Communications.

REFERENCES

[1] E. Istrate and E.H. Sargent, “Photonic crystal heterostructures – resonant tunneling, waveguides and filters”, J. Opt. A: Pure Appl. Opt. 4, S242 (2002).
[2] A. Sharkawy, S. Shi and D. W. Prather, “Heterostructure photonic crystals: theory and applications”, Appl. Opt. 41, 7245 (2002).
[3] B.-S. Song, T. Asano, Y. Akahane, Y. Tanaka and S. Noda, "Transmission and reflection characteristics of in-plane hetero-photonic crystals", Appl. Phys. Lett. 85, 4591 (2004).
[4] B.-S. Song, S. Noda, T. Asano, and Y. Akahane, “Ultra-high-Q photonic double-heterostructure nanocavity”, Nature Materials 4, 207 (2005).

III. SPATIAL FIELD DISTRIBUTION

Because the spatial electromagnetic field distribution associated with a bound state consists of the product of the periodic part of a Bloch waveguide field and a localized exponentially decaying envelope, the peaks and zeros of the fields are determined by the particular orientation of the PC air holes. Fig 1 displays schematic diagrams of two PCDH cavities both created by perturbing 2-3 PC air holes. The left side of Fig 1 shows an odd number of PC air holes adjacent to the PCWG core, whereas on the right, there are an even number of air holes adjacent to the core. The WG field consists of nulls at air holes and peaks between air holes. This suggests the ability to control the placement of nulls and peaks in the cavity which could be beneficial for reducing out of plane radiation when double-heterostructure cavities are clad above and/or below with materials with higher indices of refraction than air. We have obtained numerical $Q$'s a factor 5 larger for cavities with a null in the center over cavities with peaks in the center for PCDHs placed on high index posts.

Figure 4. (a.) Group index as a function of normalized frequency for solid line: single line defect PCWG, dashed line: PCDH cavity (b.) Top line: experimentally measured resonance spectrum from PC double heterostructure cavity with -2.5% lattice constant perturbation, bottom line: spectrum obtained numerically for same device.

Figure 5. (a.) Real[$E_z$] peaked in the center. (b.) Real[$E_z$] zero at center.

1Department of Electrical and Computer Engineering
Boise State University
1910 University Dr.
Boise, ID 83725