**Asymmetrical resonant cavity thin film devices designed for vanadium dioxide applications**

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**Abstract**:Various Vanadium dioxide thin film devices with different use cases are redesigned to introduce an asymmetrical resonant cavity structure. The redesign devices are variant of asymmetrical distributed Bragg reflector (DBR). The advantages, limitations and problems of such a design are discussed.

**Keywords:** optical thin film, thin film design, vanadium dioxide

1. Introduction

Phase change materials (PSMs) are materials that change their crystal structure when sufficient thermal energy is applied. This significantly alters their properties, for example, the real and imaginary refractive index. Researchers have used the change in these properties to design a device that change its optical indexes based on temperature. For example, a thermochromic windows coating that change its reflection property in the infrared spectrum based on its temperature [1]. Or a limiting optical diode that while ‘on’, allows light to travel freely in both directions but will ‘turn off’ and acts like a filter to protect the sensitive light source when heated sufficiently [2]. VO2 was chosen as this study PSM because of its volatile nature. It also has the lowest phase change temperature at 68 °C compared to other popular PSMs. This is in the hope of finding real world use cases for the redesigned device.

Resonant cavity design allows lights(photons) to cycle through the central cavity layer(s) multiple times. It’s mainly used for line-pass or band-pass filters. But a problem will occur when we design a device with PSMs. This is because, compared to dielectric layer(s) normally used, PSMs have higher imaginary refractive index which will result in the loss of resonant when substituting cavity layer that’s made of dielectric with PSM. Previously, the solution was to use a genetic algorithm [3] or use numerical optimization to get an approximation [4] both of which can’t give a solution when given a desired resonant wavelength, and materials index. To solve this, Saragan, A. introduced a new design approach. By modifying distributed Bragg reflector (DBR) resonant cavity structure with asymmetrical reflector layers [5]. This allows us to get a solution for any given resonant wavelength, or materials index.

In this paper, many Vanadium dioxide (VO2) devices are redesigned to use the asymmetrical resonant cavity structure. The results are then compared to the originals, particularly the transmission, reflection and absorption properties, the difference in VO2 used, and the total thickness of the devices. The purpose of which is to find a use cases for asymmetrical resonant cavity thin-film designs.

2. Theory

Traditional DBR resonant cavity structure is composed of a central cavity layer sandwiched between two reflector layers on each side. The central cavity layer is used for its refractive index, which will determine the resonant frequency and the optical property of the device. It’s usually made of dielectric materials but can also be PSMs or metals. The two reflector layers will help the lights cycle through the central layer multiple times. Because the central cavity layer is reused multiple times, the device’s optical properties, mainly its absorption and transmission, at the resonant wavelength will be enhanced greatly. We want the design to be antireflection. So, each reflector layer will consist of (multiple) unit cell(s) with quarter-wave thick films of high (H) and low (L) refractive index. Each unit cell has notation of [H/2 L H/2], where H/2 denoted a half quarter-wave thick film. Normally, the number of unit cells used on each side is symmetrical. We can then make the structure exhibit an antireflection property by placing H/2 films on the outside of each reflector layer. We do this because reflectivity is not useful to most applications mentioned. The final structure will have a notation of H/2 [U]N [D] [U]N H/2, where U is a unit cell, N represents the number of unit cells, and D represents the central cavity dielectric layer.

To make the devices behave differently depending on the temperature, we will use PSMs as a cavity layer. This is because of the high imaginary refractive index in PSMs, which essentially mean PSMs can absorb light and turn it into other forms of energy, mainly heat. By substituting the dielectric layer with PSM. And if the refractive index of PSM have a small imaginary index, like a typical dielectric material used in the design, this won’t cause a problem in resonant shifting. But in practice, all PSMs have a large enough imaginary index that a simple substitute will cause the resonant to be shifted significantly. This will then cause the optical properties of the structure to changes from the design significantly. As for the methods mentioned in the introduction, neither method can give the solutions for an exact thickness of each layer when given a targeted wavelength and the materials refractive index. This will be a problem for cases like an optical diode [2] mentioned above or a similar, self-activating optical limiter device [6] that’s designed for a particular(targeted) wavelength.

To solve this problem, we can modify the structure to be asymmetrical in term of number of unit cells used on each side of the reflector. This will result in an asymmetrical resonant cavity structure [5] that can compensate for materials with high imaginary index. The new structure will have a notation of H/2 [U]N [C] [U]M H/2, where C represents the central cavity complex layer (PSM in this case), N represent the number of unit cells in the transmission (back) side, and M represent incident (front) side. The central cavity layer can be modified with additional D(s) and C(s) depending on the use cases.

3. Results and Discussion

Table 1. Comparison of the originals and the redesigned devices. The redesigned layouts shown are the central cavity layer. N and M represent the number of [H/2 L H/2] unit cells in the back and front side respectively.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Reference | Wavelength (nm) | Layout | Transmission | | | Absorption | | Reflection | | VO2 used (nm) |
| **on** | **off** | **ratio** | **on** | **off** | **on** | **off** |
| **[2]** | **1320** | **C Au(10nm)** | **0.22** | **0.03** | **7.7** | **0.14** | **0.18** | **0.64** | **0.80** | **100.0** |
|  |  | [C D C] N=5, M=4 | 0.41 | 0.08 | 5.3 | 0.59 | 0.39 | 0.00 | 0.53 | 2.8 |
|  |  | [C D C] N=4, M=3 | 0.41 | 0.08 | 5.1 | 0.59 | 0.39 | 0.00 | 0.53 | 7.0 |
|  |  | [C D C] N=3, M=2 | 0.41 | 0.09 | 4.5 | 0.59 | 0.40 | 0.00 | 0.51 | 18.6 |
|  |  | [C D] N=4, M=3 | 0.38 | 0.06 | 6.0 | 0.62 | 0.38 | 0.00 | 0.55 | 8.5 |
|  |  | [D C] N=4, M=2 | 0.22 | 0.02 | 9.2 | 0.78 | 0.02 | 0.00 | 0.63 | 36.5 |
| **[6, 8]** | **1550** | **Au(6nm) C** | **0.49** | **0.13** | **3.7** | **0.17** | **0.21** | **0.34** | **0.66** | **52.0** |
|  |  | [C D C] N=5, M=4 | 0.41 | 0.04 | 10.4 | 0.59 | 0.29 | 0.00 | 0.67 | 5.2 |
|  |  | [C D C] N=4, M=3 | 0.41 | 0.04 | 9.5 | 0.59 | 0.29 | 0.00 | 0.66 | 13.2 |
|  |  | [D C] N=5, M=4 | 0.42 | 0.04 | 10.7 | 0.58 | 0.30 | 0.00 | 0.66 | 5.3 |
|  |  | [D C] N=4, M=3 | 0.44 | 0.04 | 10.3 | 0.56 | 0.30 | 0.00 | 0.66 | 13.6 |

For the optical limiting devices. The best redesigns of ref [2] and [6] are shown in Table 1. Because of the antireflection design, each redesign has a better or comparable transmission and absorption value in the ‘on’ state. The increased transmission value will make the device more efficient, and the increase in absorption value will decrease switching time. And because of the two reflector layers, the redesign use significantly less VO2. To note, the ratio between the transmission and absorption, which will affect the amount of time and thermal energy it took for the devices to undergo phase change, wasn’t considered.

As for the thermochromic windows coating (not shown here). The largest challenge for real-world adoption is in the high phase change temperature, not the device design [2, 9]. And because of the large surface area and the commercial intent, it’s in the author’s opinion that the complexity of the redesign device outweighs any benefit it gave. There have been a review of the effect of elemental doping on the optical properties of VO2 [7], which is better suited to solve this challenge.

The main advantage of this design method is less VO2 used, while having equal or better transmission. The limitation is the narrow operating bandwidth, which limited the use case to narrow wavelength e.g. laser. The disadvantages are the complexity of fabricating multiple reflector layers, which will also cause the overall device to be thicker than the originals, and the sensitivity to the PSMs thickness. For a large N and M values, a few nanometers difference from the design could cause the resonant wavelength to be shifted significantly.

4. References

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